Assignment: "Magnetic storms and substorms: The role of convection and substorm electrojets, particle precipitation, plasma convection and global current systems during geomagnetic active periods. Focus on recent scientific studies: state of the art, open questions, which are the main achievements and open challenges."

Bruce T. Tsurutani*, Rajkumar Hajra, Gurbax S. Lakhina,

Anthony J. Mannucci, Ryan Mcgranaghan, Xing Meng

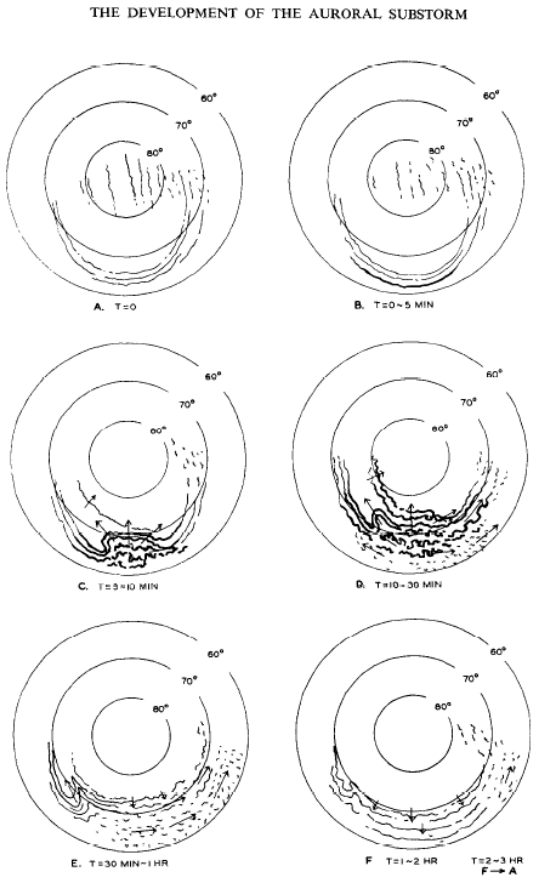
Bruce.Tsurutani@jpl.nasa.gov; rajkumarhajra@yahoo.co.in;gslakhina@gmail.com; Anthony.j.Mannucci@jpl.nasa.gov;ryan.Mcgranaghan@jpl.nasa.gov;xing.meng@jpl.nasa.gov

*Jet Propulsion Laboratory, California Institute of Technology, Pasadeana, CA

Comments/Introduction

- First we will mention that magnetic storms and substorms are typically externally driven. So we will briefly mention the mechanisms for external driving and solar cycle dependences.
- When one discusses external driving, it is obvious that there are other mechanisms that lead to ionospheric current systems, particle precipitation and ionospheric TEC enhancements and decreases. So these phenomena will be discussed briefly as well.
- The presentation and some references will be made available to the SWARM community. Please contact any of the authors if you have additional questions or for ideas of data analyses projects. They have all agree to help, if asked.

Akasofu coined the term "substorm". His thesis advisor Sydney Chapman insisted that he use this term or else he wouldn't be allowed to publish.



Brightening of equatorward most loop

Breakup and expansion

The typical time scale is ~15 min to 1 hr

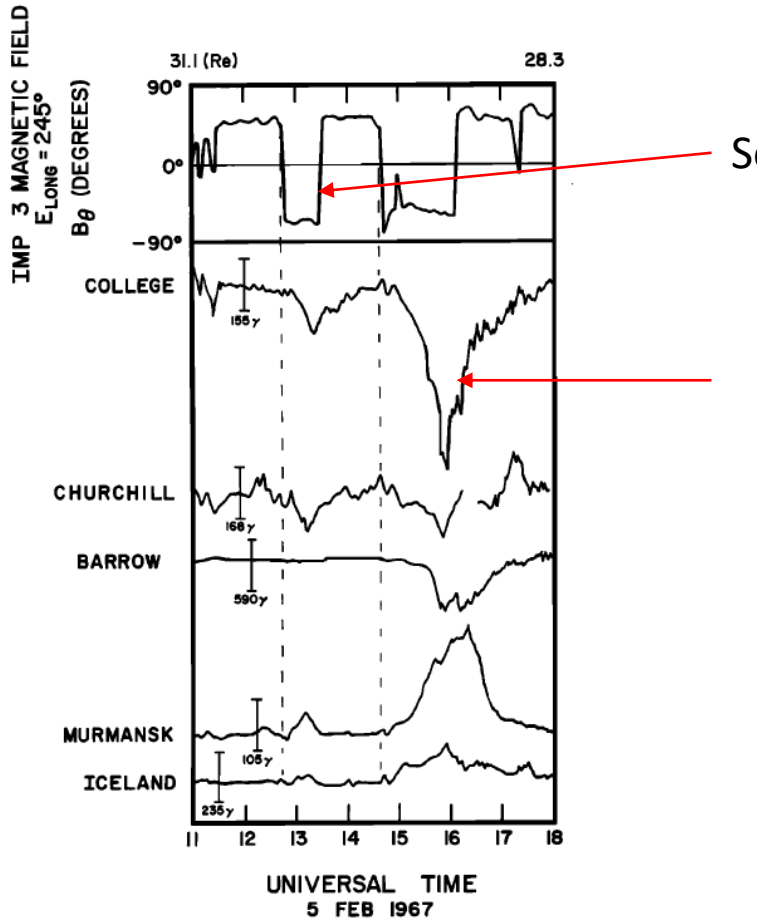
Recovery

Comment: Not much has changed since the original Akasofu substorm concept. Some people Are studying substorms triggered at the most poleward arc (see also Rostoker). A further comment will be made later.

Akasofu, PSS 1964

The typical cause of isolated substorms is magnetic reconnection (Dungey, PRL 1961) associated with the southward Bz component of interplanetary Alfvén waves.

Tsurutani and Meng, JGR 1972



Southward IMF Bz

Substorm

Comment: auroral arcs (upward field aligned-currents) are associated with the precipitation of ~0.1-10 keV electrons which create Ionization at the ~100 -120 km altitude range. Diffuse auroras are due to the precipitation of ~10-100 keV electrons which penetrate down to ~80 km altitude.

Substorm Problems

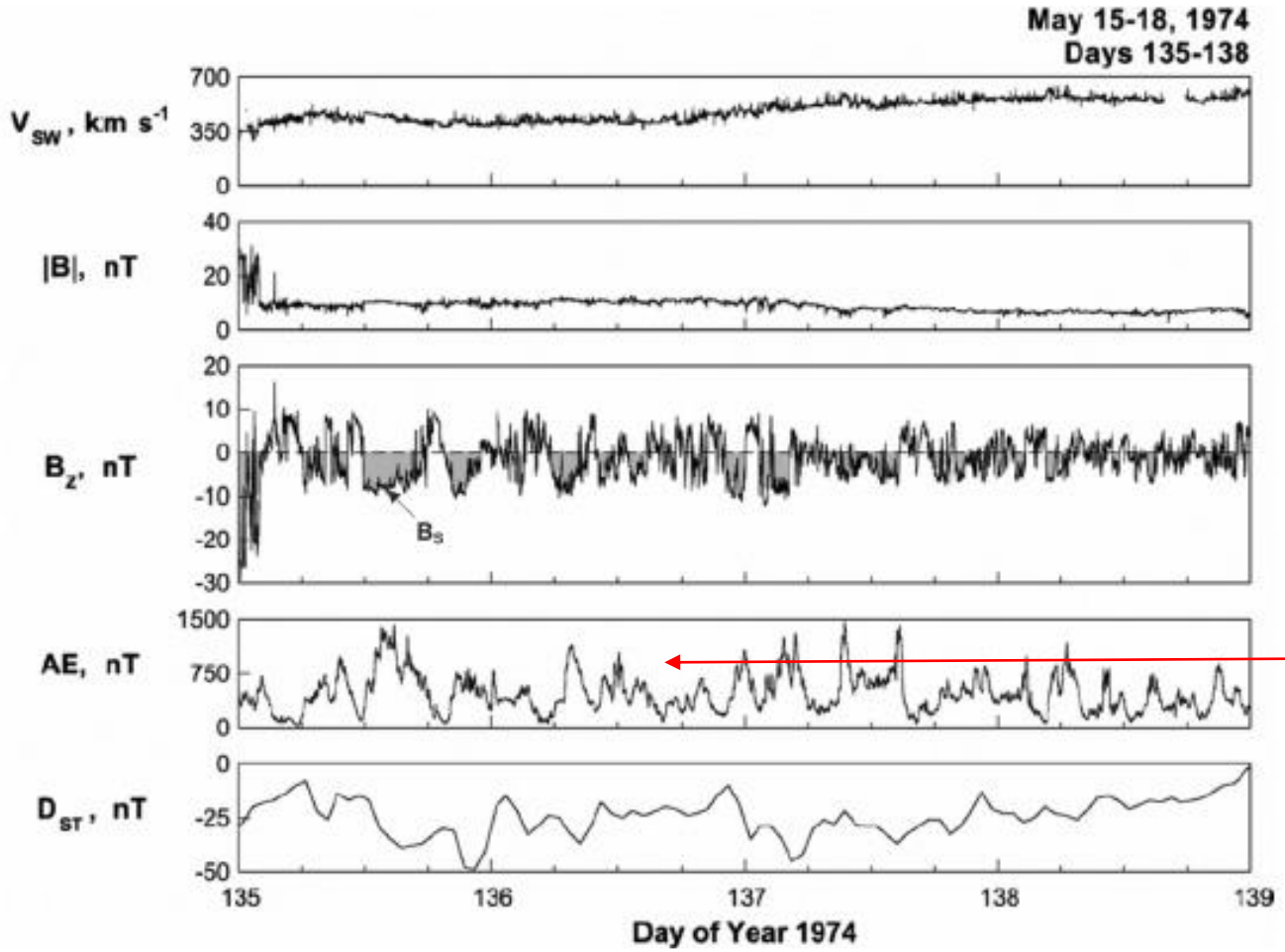
Although the Akasofu 1964 scenario is “well accepted”, in a recent private conversation with me, he mentioned that this scenario is actually one of “typical features”, not one of repeatable “check-list” items.

So one question is what are the variations from this norm, how frequently do they occur and are they externally or internally driven?

Are Substorms An Incremental Unit of a Magnetic Storm?

- From the title given to us, it is clear that the organizers realized the possibility that the answer is “no”. This is also my answer.
- We will show that substorms can occur without magnetic storms and magnetic storms can occur without substorms.

An Example of Substorms Without Magnetic Storms: High-Intensity Long-Duration Continuous AE Activity (HILDCAAs): A series of substorms and "convection" events. These typically occur in a CIR storm "recovery phase". By definition, they are restricted to occur outside of a storm main phase.

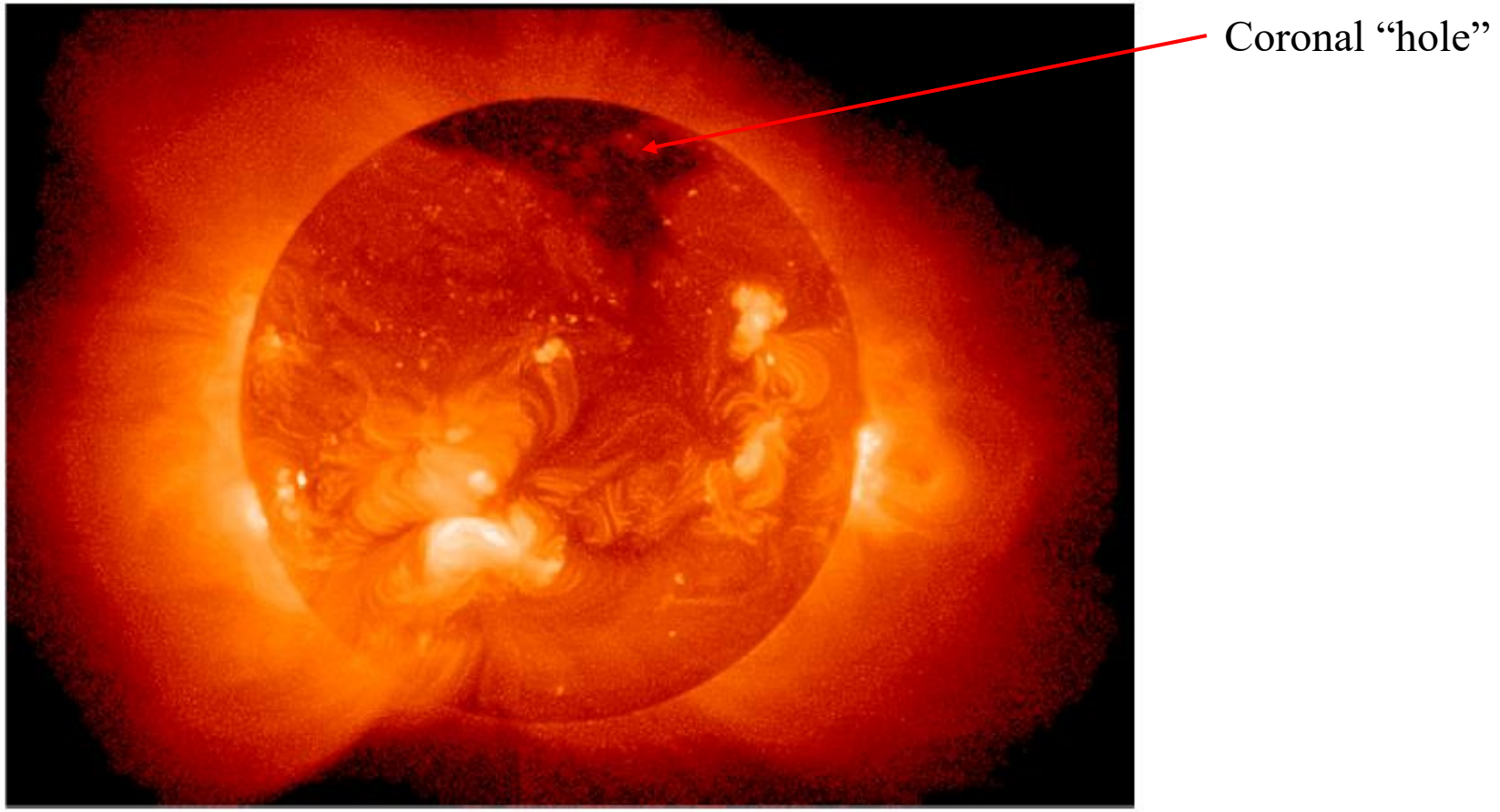


A train of Alfven waves

A HILDCAA

Tsurutani and Gonzalez, PSS, 1987; Tsurutani et al. JGR, 1995, JASTP 2004, JGR 2006; Hajra et al. JGR 2013, 2014

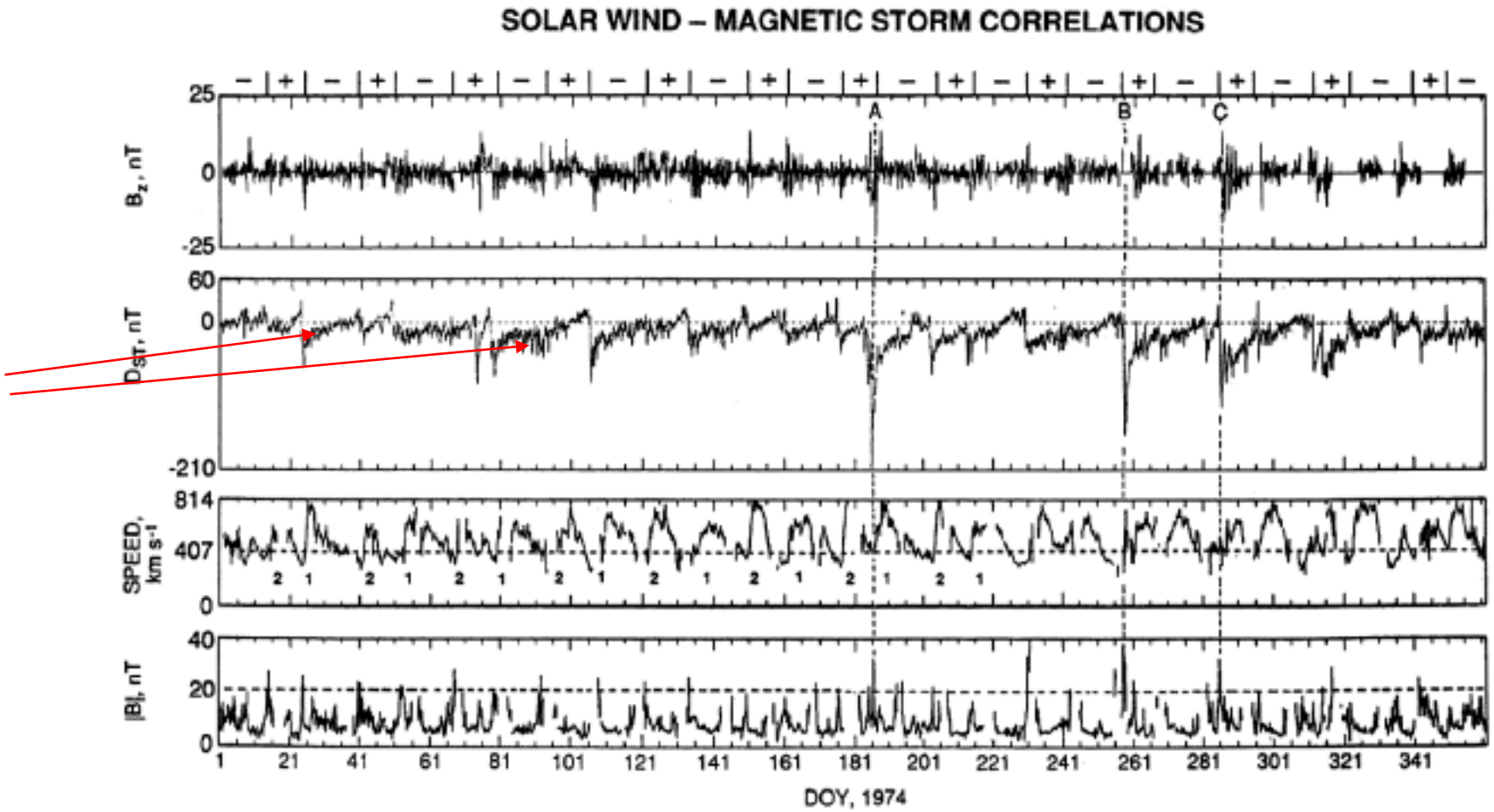
The source of most HILDCAAs: High speed solar winds emanating from solar coronal holes. This is a solar cycle declining phase phenomenon (Hajra et al., JGR 2014; JASTP, 2014)



~27 day recurrent storms first discussed by Maunder (MNRAS 1905, 1906) and Chree, TMAE 1911. These are the Bartels “M-regions” (1934).

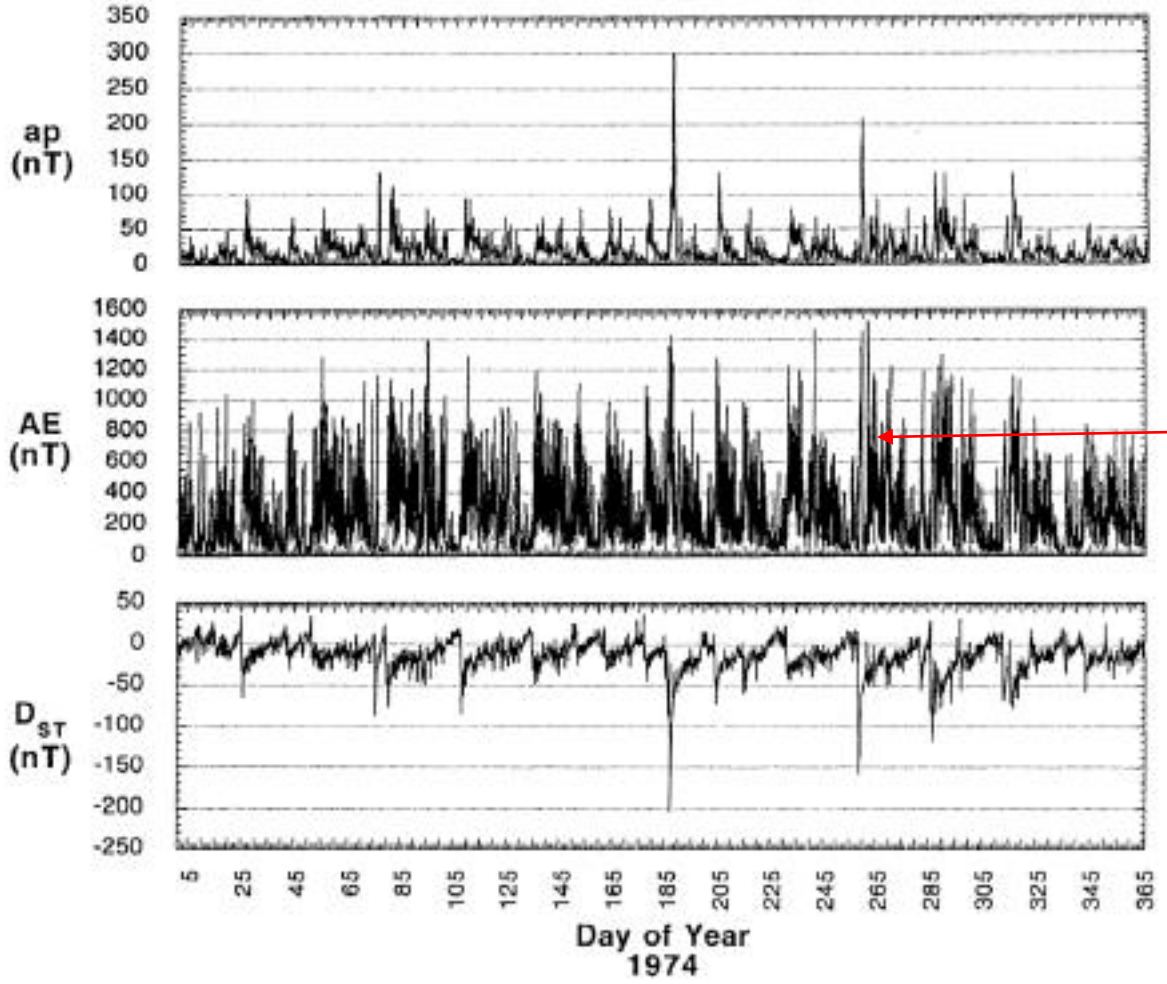
1973-1975 was a highly unusual period where HILDCAAs were almost continuously present. Will this happen again in the near future?

HILDCAAs



Tsurutani et al. JGR 1995

AE is continuously high for all of 1973-1975. There were two long-duration coronal holes, one at the north solar pole and one from the south.

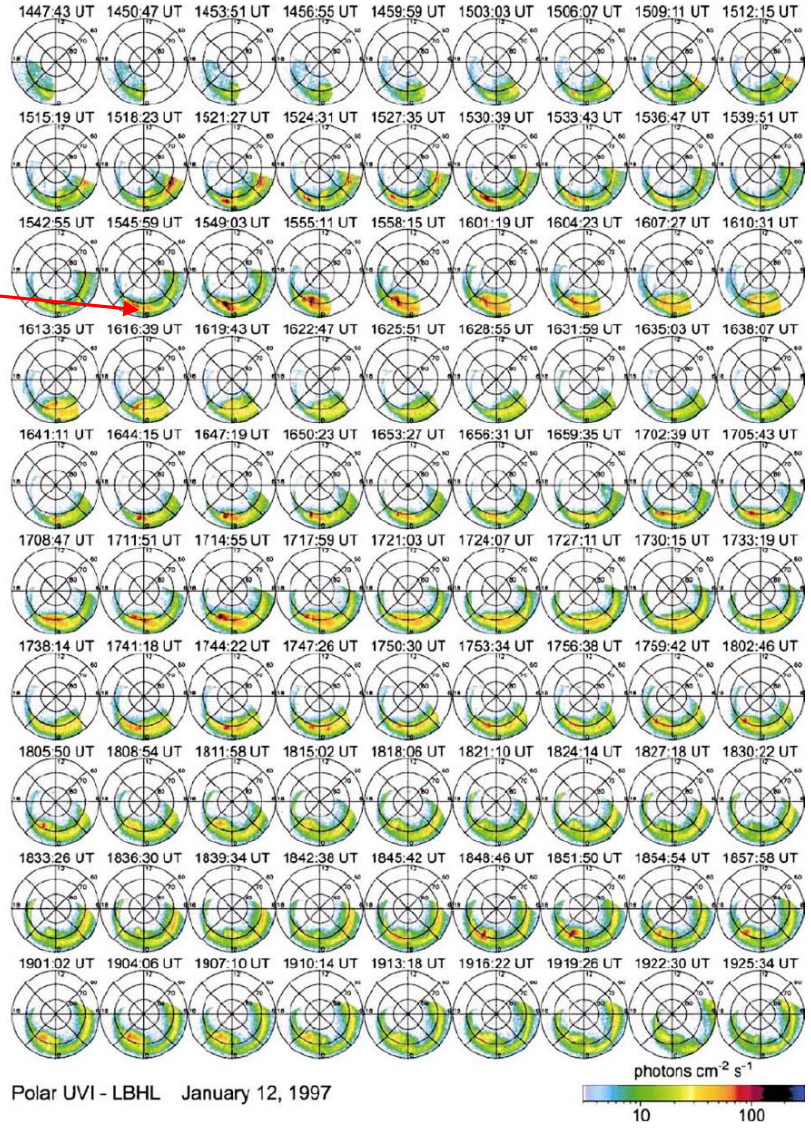


Extremely high annual AE

The integrated energy of HILDCAAs over ~4 days is higher than that for ICME magnetic storms (Turner et al. 2006, Guarnieri, 2006, Kozyra et al. 2006, Gonzalez et al. 2006: all in AGU monograph vol. 167; Hajra et al., JASTP 2014, JGR 2014).

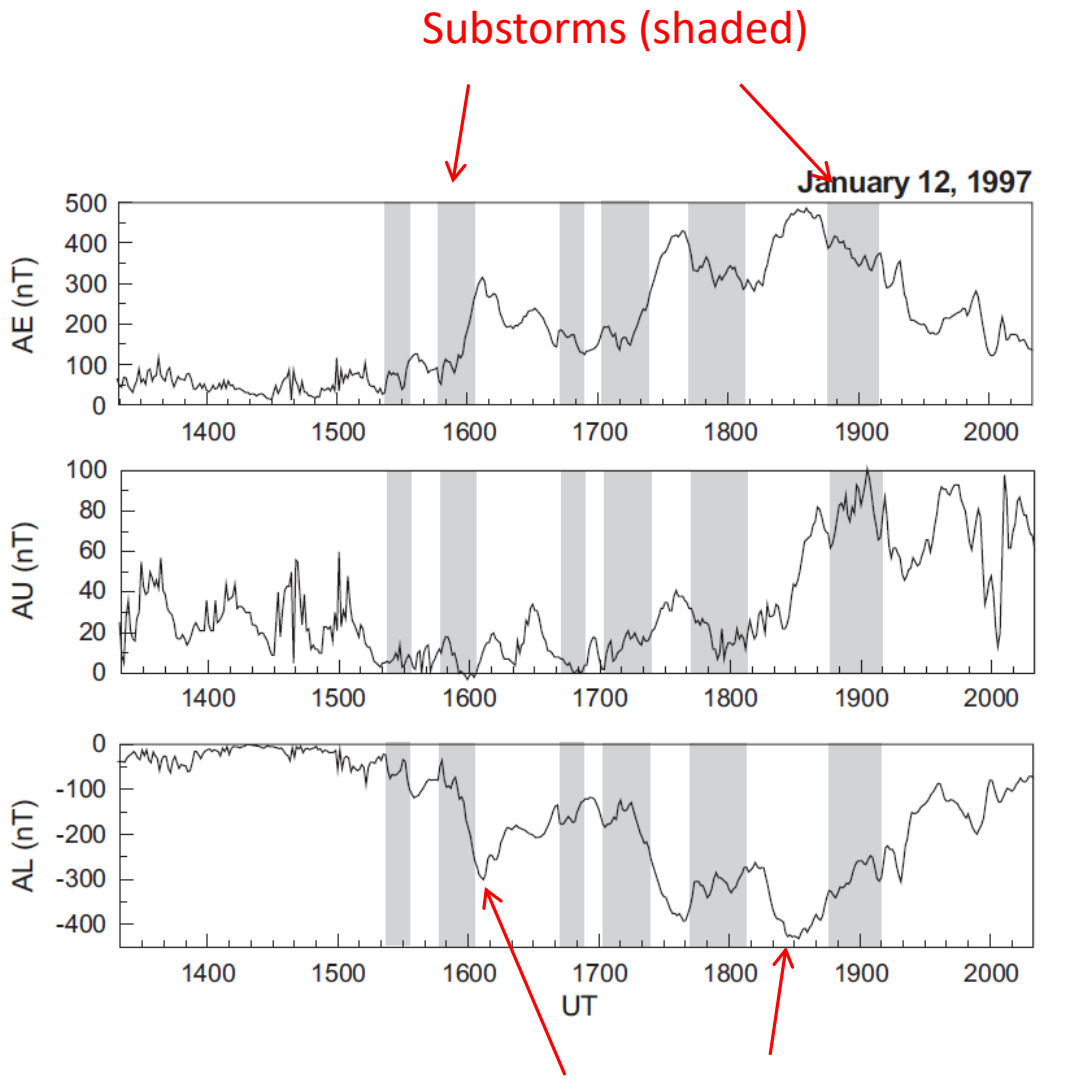
Substorm Expansion Phases Are Identified from POLAR UV Image

substorm



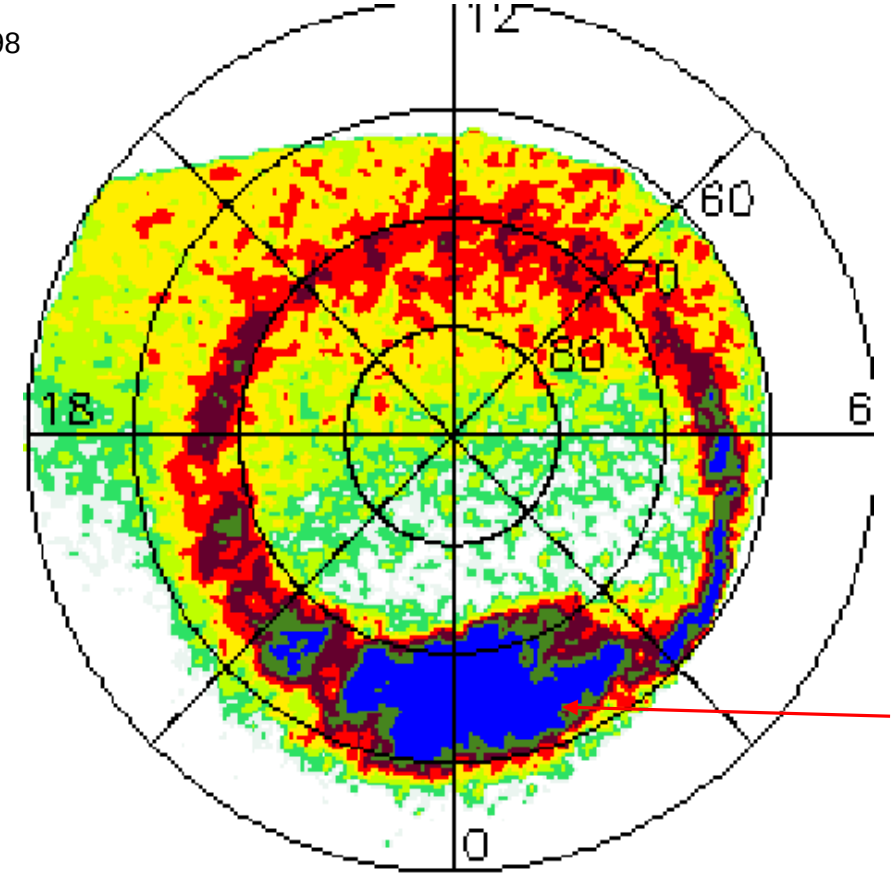
Tsurutani et al. JASTP 2004

However Optical Substorms are Not Well Correlated with AE (During HILDCAAs)!



HILDCAA Auroras: Entire Auroral Zone, Sometimes Including the Polar Cap

July 24, 1998



Substorm intensification

Guarnieri, AGU Mon, 2006; Guarnieri et al., 2007

Ionospheric Disturbance Dynamo

Thermospheric winds produced by auroral heating (during magnetic storms) and their global dynamo effects.

Blanc and Richmond, JGR 1980

Questions About HILDCAAs that SWARM could address

What are the “convection events” that are apparently not substorms (see Tsurutani et al. JASTP, 2004)?

HILDCAA auroras occur in the auroral zones at almost all local times (including the polar caps). What is the field-aligned current distributions for such cases?

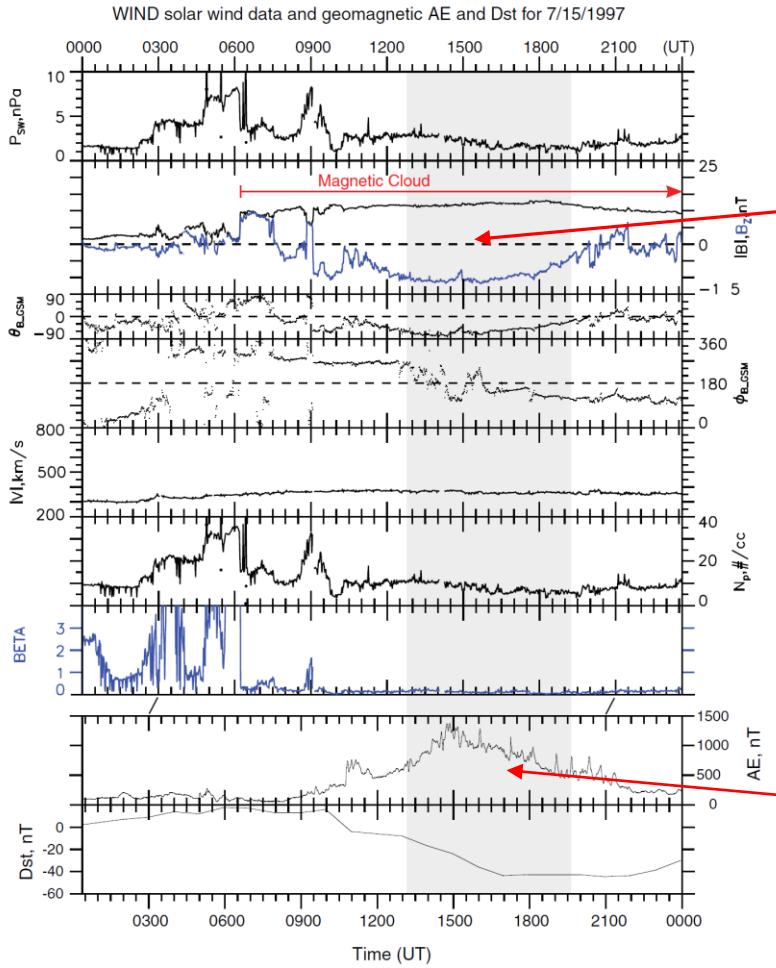
What is the effect of the precipitation? Is there a major “disturbance dynamo”? Is there a steady state? Is the dynamo effect present equally in local daytime as at nighttime?

Supersubstorms (SME* > 2500 nT)

- These particularly intense substorms appear to be externally triggered not by magnetic reconnection (Tsurutani et al. AG 2015; Hajra et al. JGR 2016).
- They may be different than the typical Akasofu smaller substorms.
- These events have been identified by their geomagnetic indices. For SWARM what is the precipitation, current and convection pattern of these events with time?

*The SME/SML indices are preferable to the AE/AL indices. SME/SML use ~300 ground stations (Newell and Gjerloev, JGR 2011; Gjerloev JGR 2012)

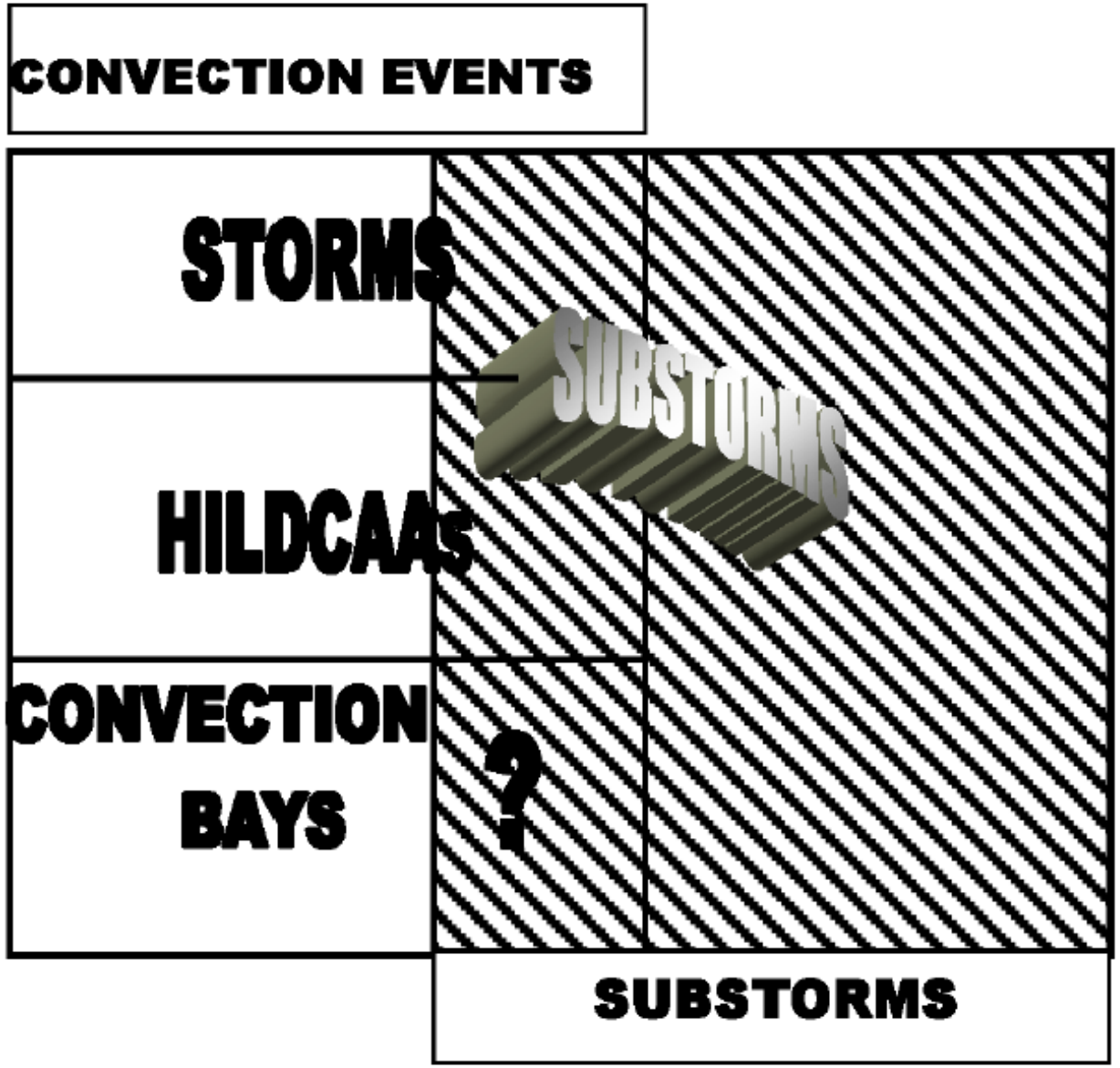
An Example of (An ICME/magnetic cloud) magnetic storm without substorms. Are these giant convection bays? What are the precipitation and current patterns during such events?



Magnetic Cloud (MC): slow rotation in IMF Bsouth

Giant convection bay? ~8 hrs long

Tsurutani et al. AGU monograph, vol. 142, 2004; Zhou et al. JGR 2004



Tsurutani et al. Adv. Geosc. 2007

Question for SWARM (and Any Other Mission)

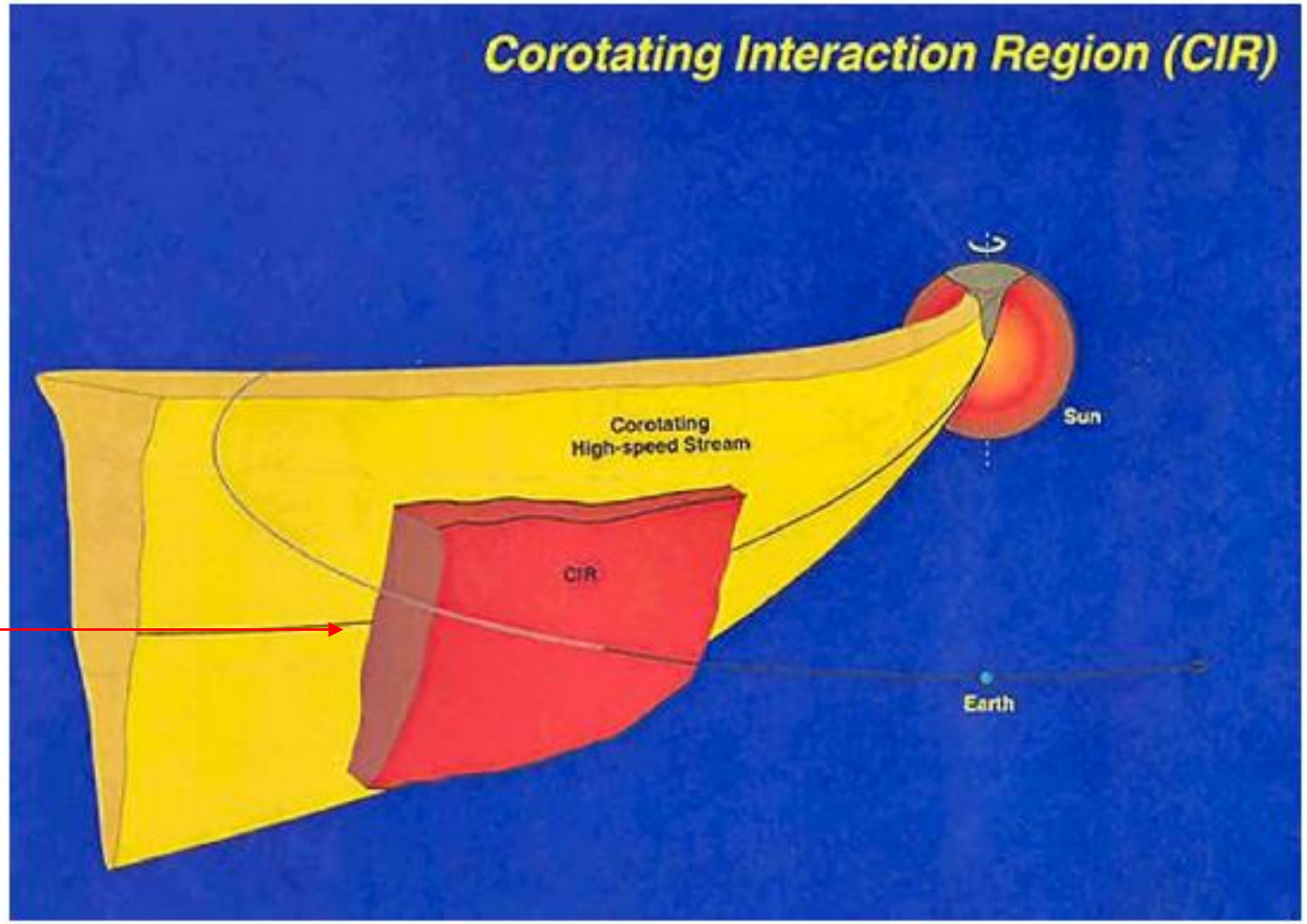
Are the convection electric fields of substorms that occur during magnetic storms superposed in the magnetosphere and ionosphere, i.e., are they two separate systems?

Are the electric fields of substorms larger (but more localized) than those of storms?

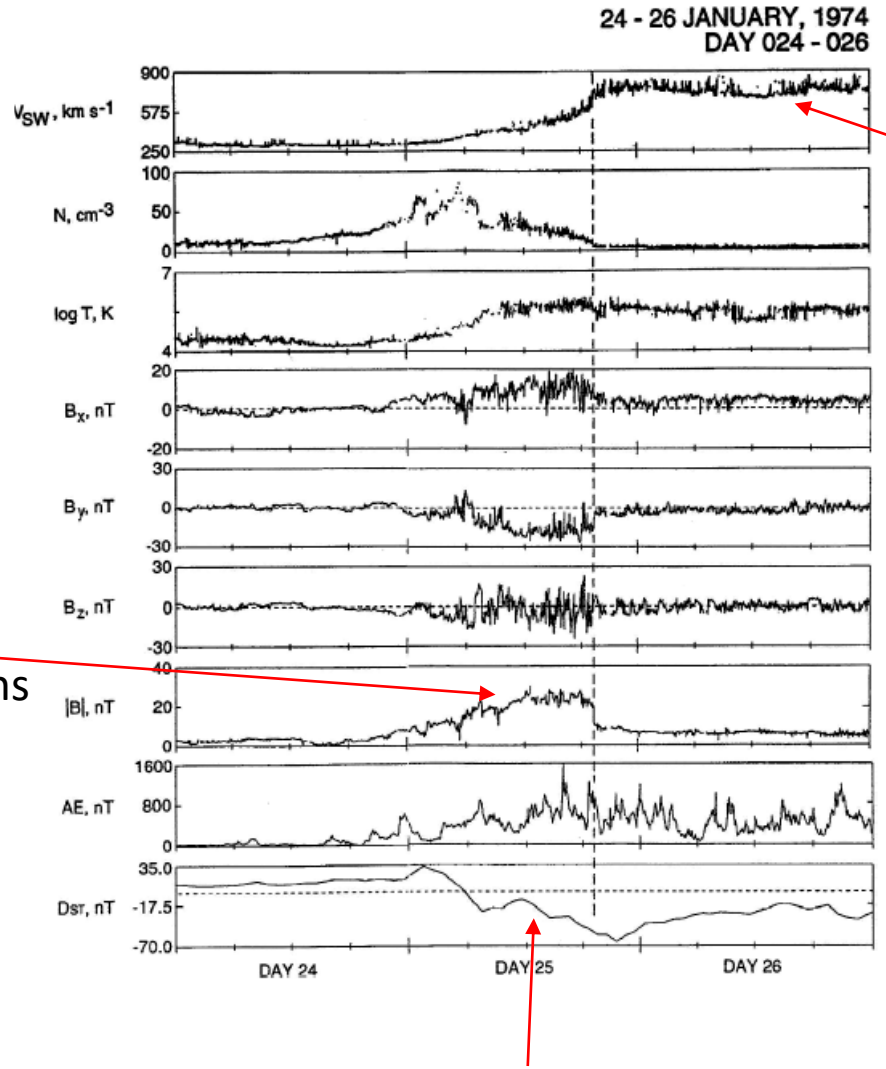
What are the current systems, precipitation and auroras for these huge convection bays?

CIRs: The Interplanetary Causes of Moderate Magnetic Storms in the Solar Cycle Declining Phase

CIRs are formed by HSS interaction with slow speed streams



A Data Example of a CIR Followed by a High Speed Stream



High speed stream (HSS): 750 to 800 km/s steady speed

CIR
Higher magnetic field strengths

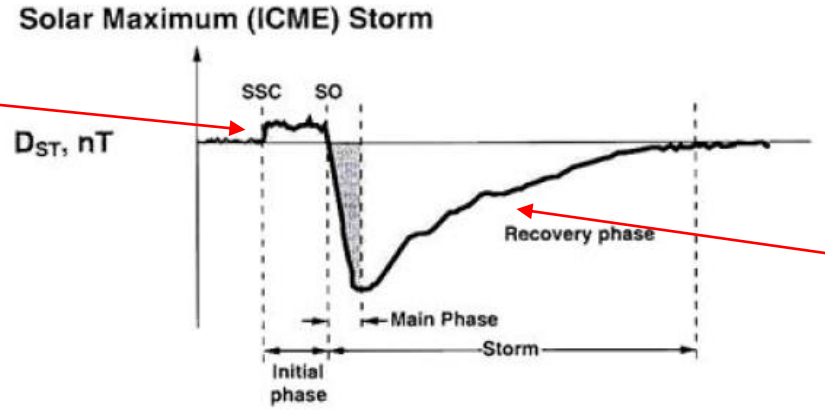
Irregular magnetic storm main phase

Tsurutani et al. JGR 2006

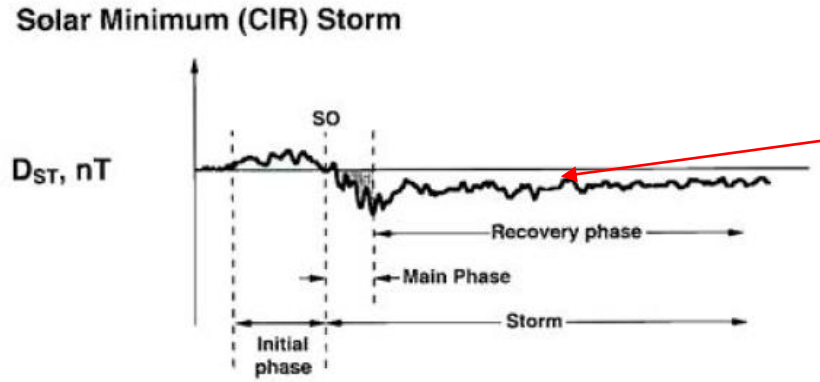
Two Types of Magnetic Storms: Identifiable by Profiles

Shock effect: Sudden Impulse (SI+)

Solar maximum or ICME-related storms



Short recovery: decay of ring current 8 to 10 hrs long



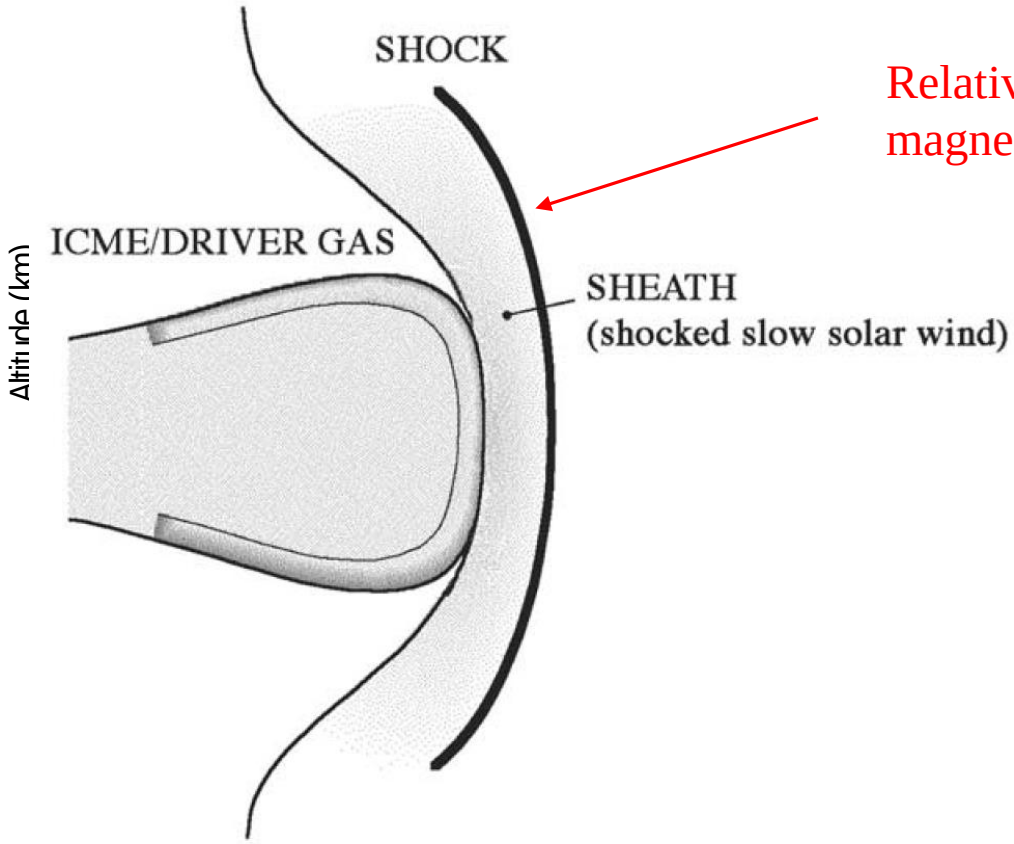
Declining phase or CIR type storms :ragged main phase, typically no shock or SI+

HILDCAA: days to weeks long

Tsurutani et al., Proc. Int. Sch. Phys. “Enrico Fermi”, edited by Coppi et al., 2001

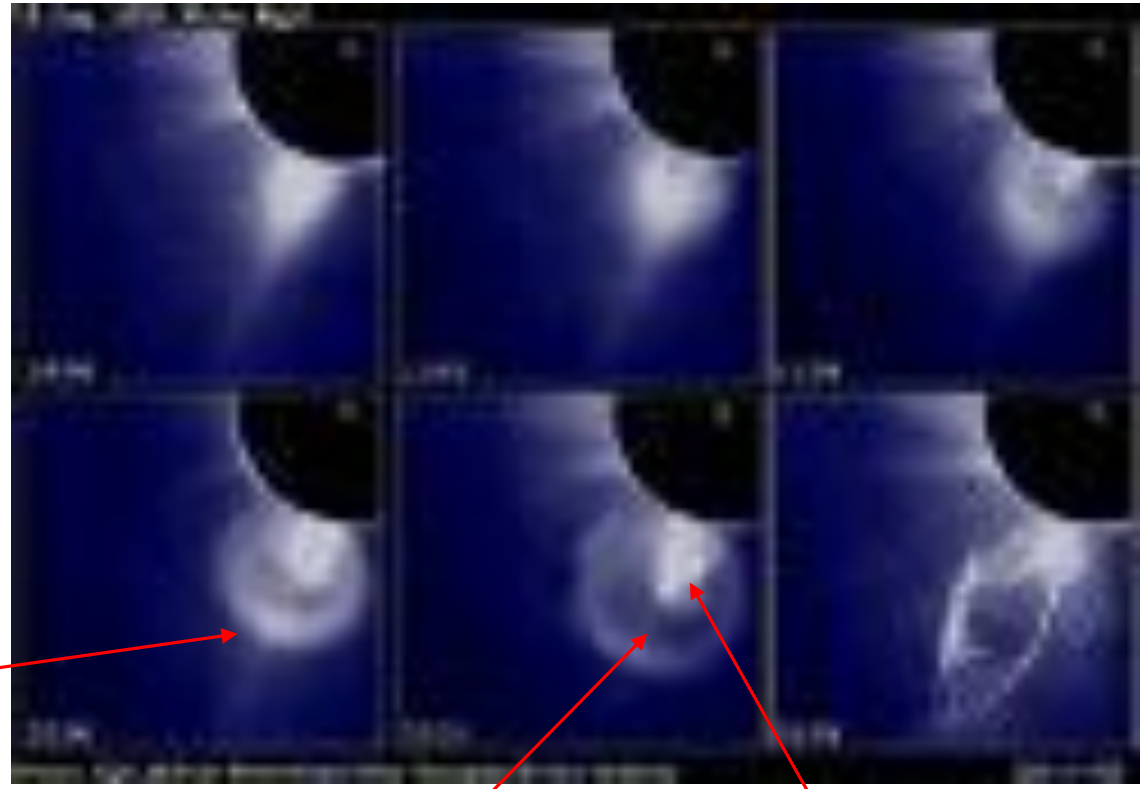
Fast ICMEs Will Produce Upstream (Fast) Shocks (and Sheaths).
The shock and sheath are created by the ICME and are not part of the ICME proper
(the sheath is shocked and compressed slow solar wind plasma and fields)

Sheath southward Bz cause an equal percentages of storms as do the magnetic cloud/driver gas magnetic fields (up to an intensity of Dst ~-200 nT)



Relative speed faster than upstream magnetosonic wave velocity

A “Coronal Mass Ejection” (CME) at the Sun is not simply a blob. There is structure that is important to geomagnetic activity



Courtesy of A. Hundhausen

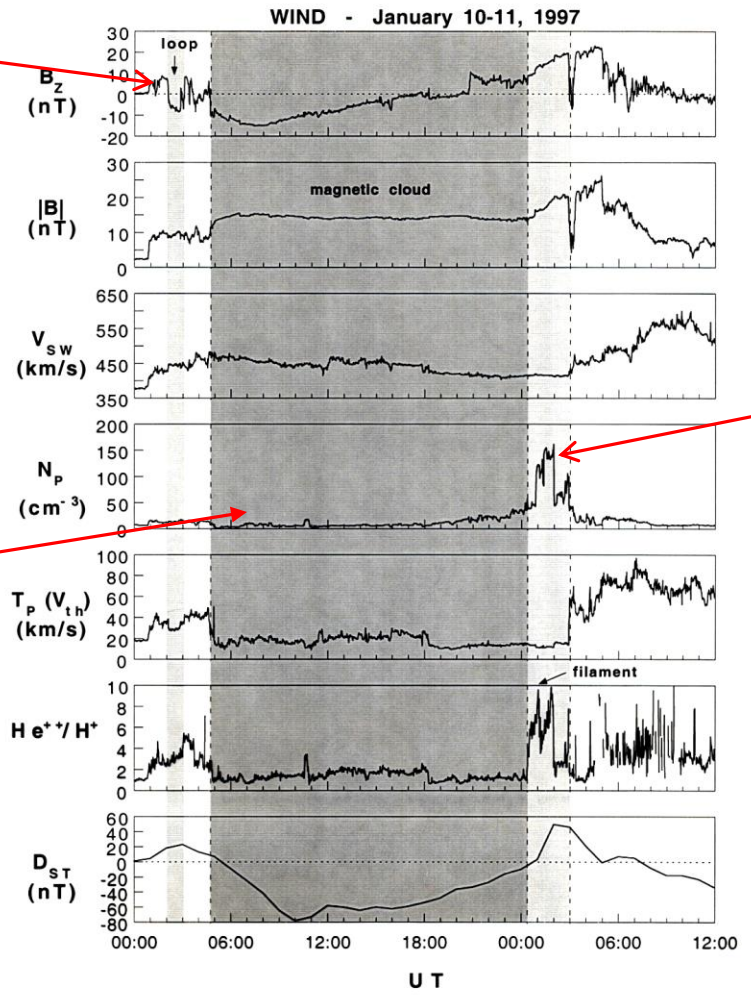
January 10-11, 1997 the only ICMEwith All three CME features?

Loop,
Tsurutani et al. GRL 1998

ICME = Loop + MC + Filament

Magnetic cloud (dark region) Burlaga et al. JGR 1981

Filament, Burlaga et al. JGR 1998

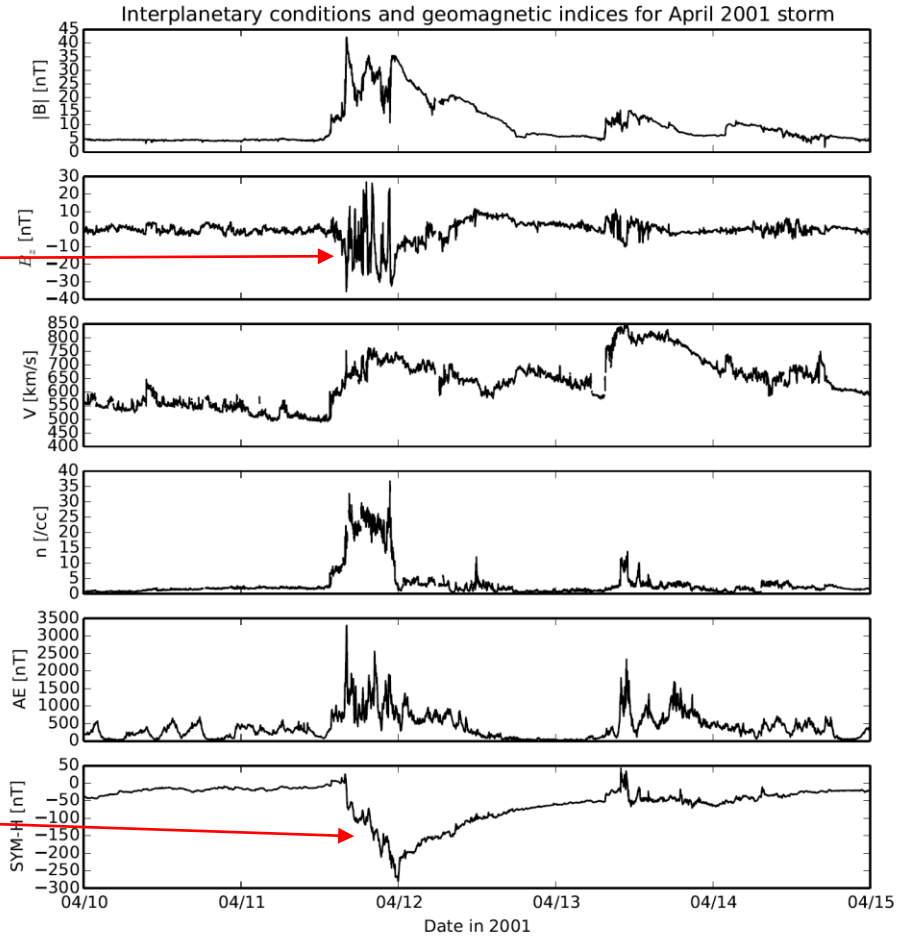


This is the only event detected at 1 AU with all 3 parts of a CME

Sheath Southward IMFs Causing a Magnetic Storm

Sheath Bz

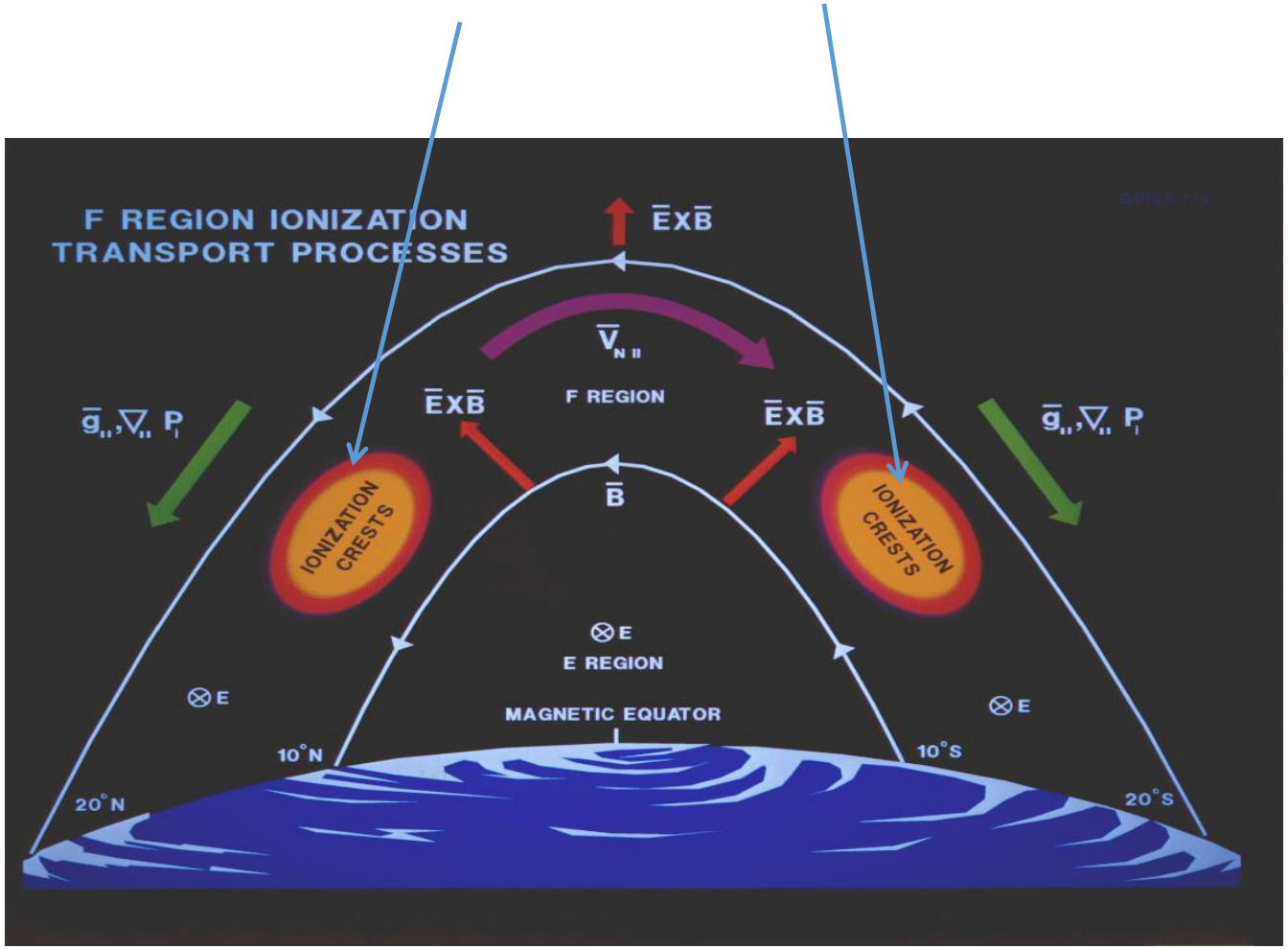
Storm main phase



Comment: All magnetic storms to date found to be caused by IMF Bz and magnetic reconnection (Echer et al. JGR, 2008)

Meng et al., in preparation 2017

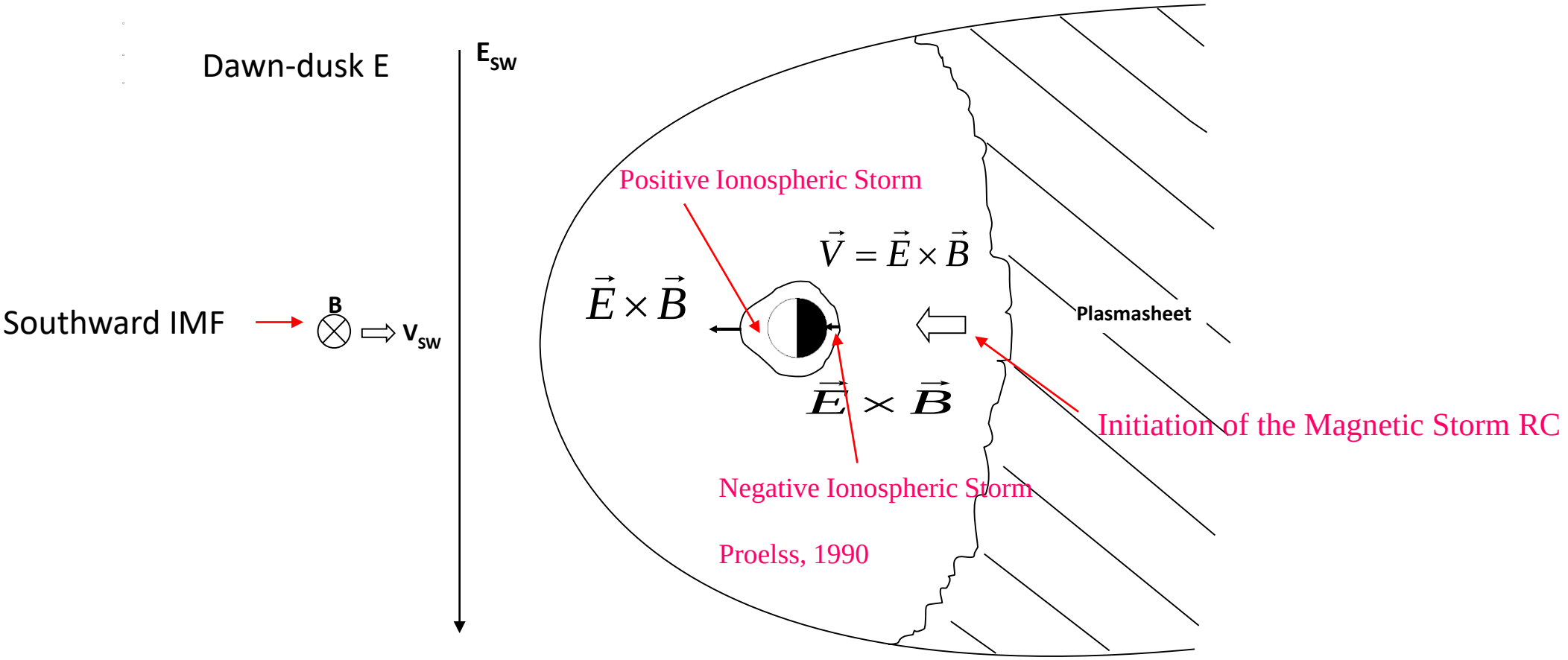
Equatorial Ionospheric Anomalies (EIAs: Used to be call Appleton Anomalies) normally located at ~ ± 10°



EIAs: Namba and Maeda, RWP 1939, Appleton, Nature 1946

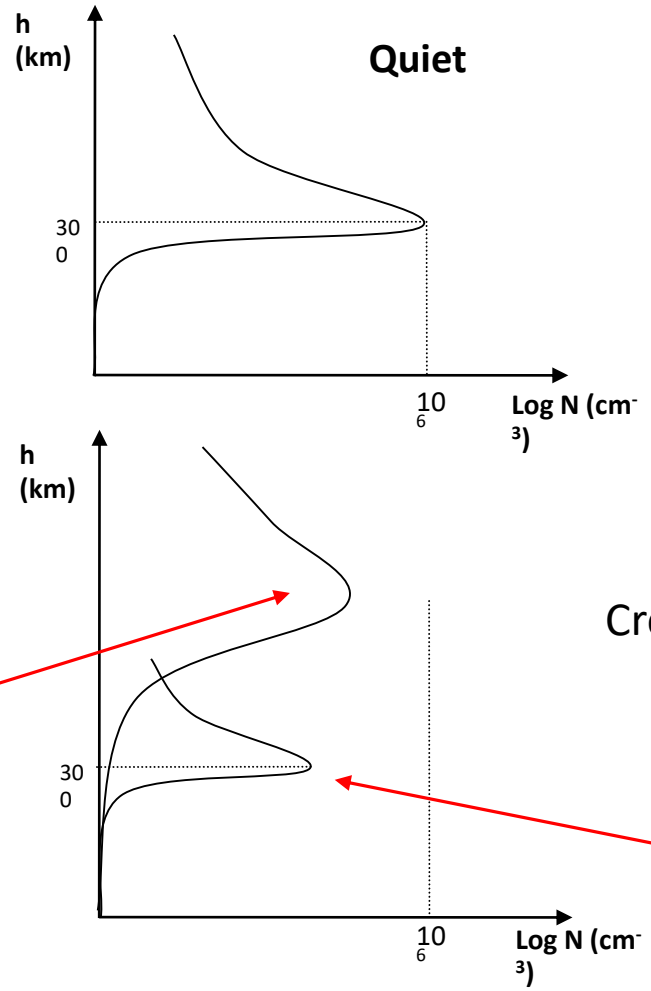
Figure from Anderson et al., 1996

Prompt Penetration Electric Fields(PPEFs) and Their Effects: A Global Scenario



Tsurutani et al., JGR, 2004, 2008

Why Ionospheric Uplift Leads to TEC Enhancements



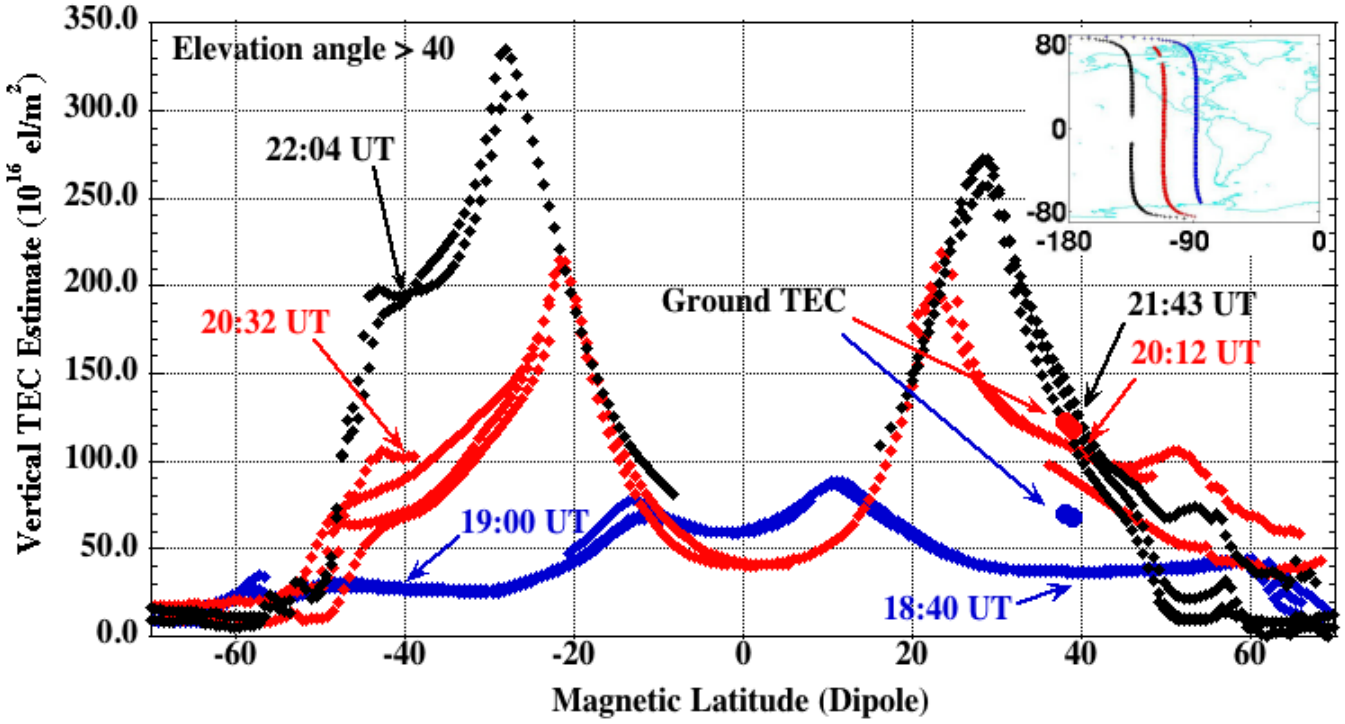
Creation of a new ionosphere: TEC enhancement

Uplifted plasma moved to region of lower recombination time scales, i.e., longer plasma lifetimes

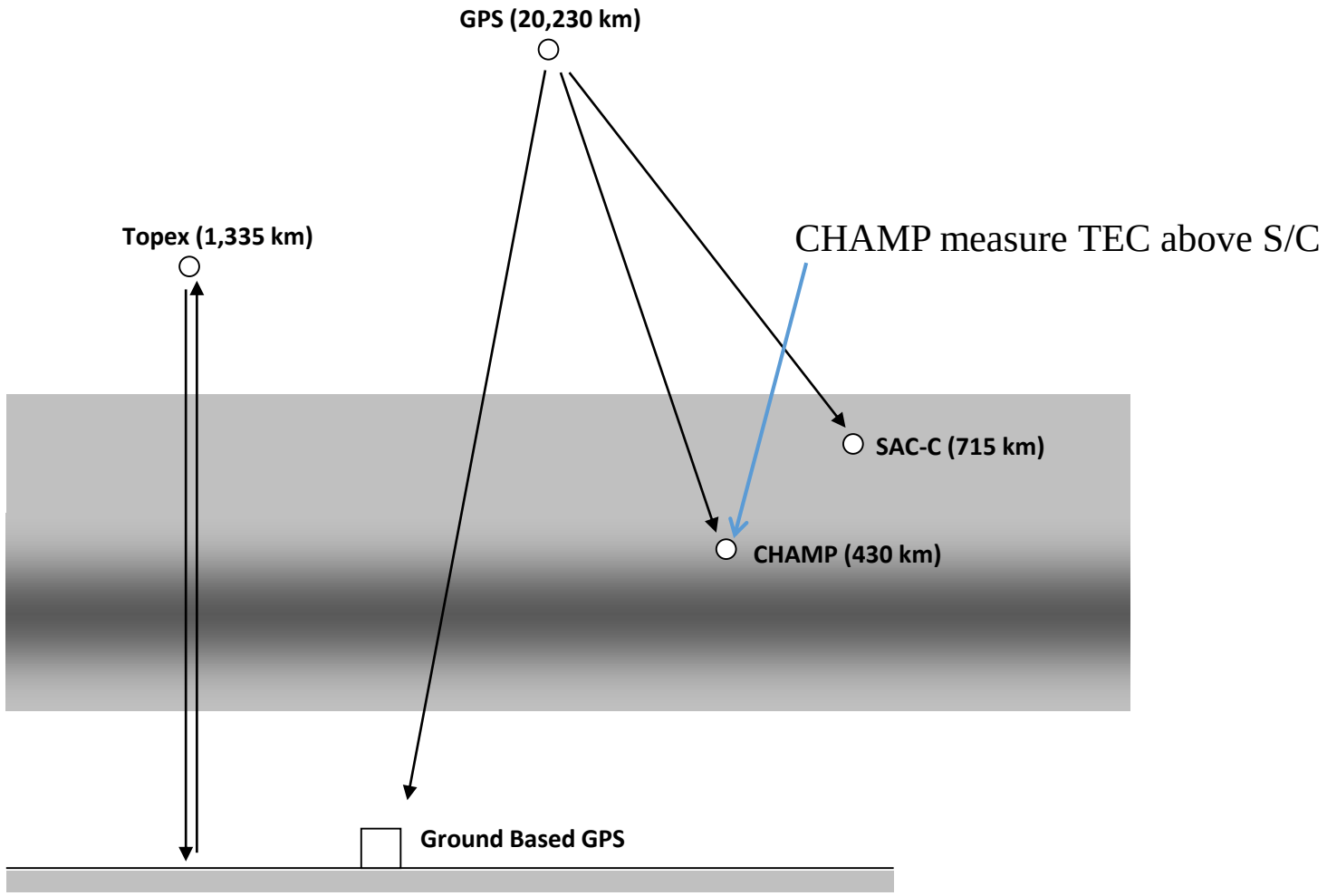
Solar photoionization creates a new ionosphere

Tsurutani et al. Ann. Geo. 2013

Prompt Penetration Electric Fields Create a "Dayside Superfountain Effect": CHAMP TEC data for Halloween Oct 30, 2003 magnetic storm



Mannucci et al. GRL 2005

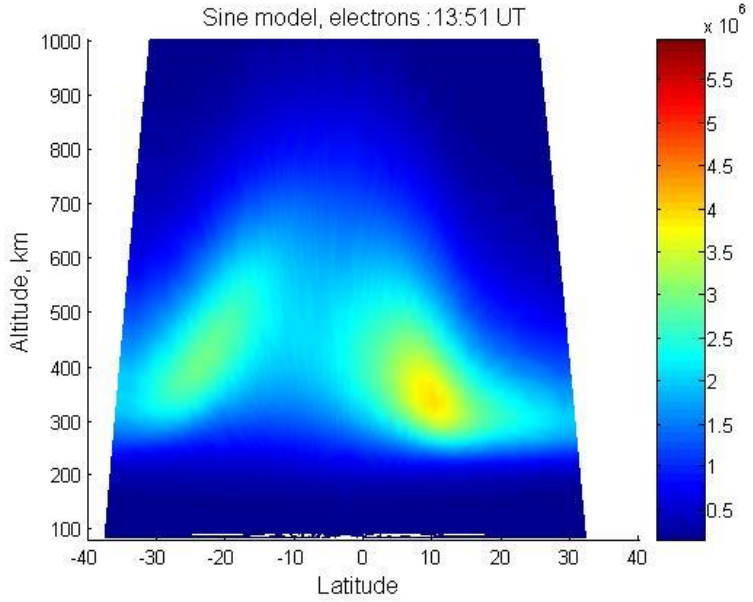

GPS (20,230 km)
Topex (1,335 km)
CHAMP measure TEC above S/C
SAC-C (715 km)
CHAMP (430 km)
Ground Based GPS

Modeling the October 30, 2003 Superstorm ”DaysideSuperfountain Effect”

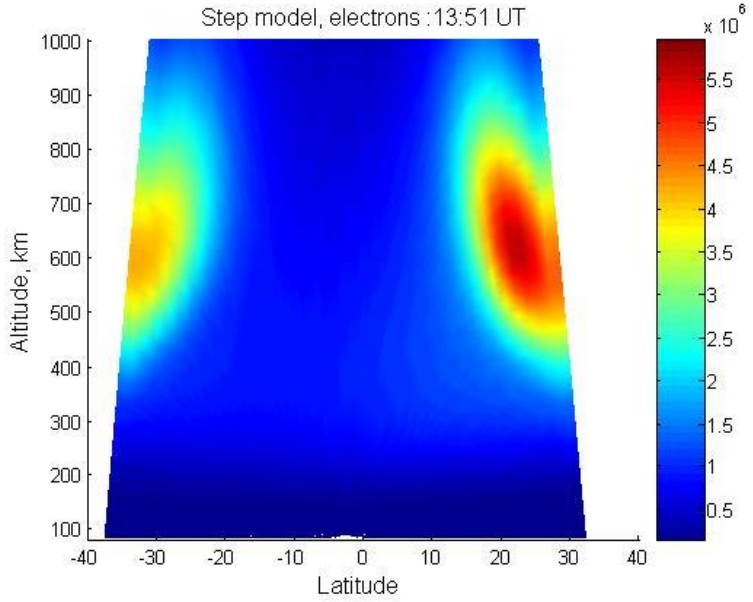
NRL SAMI-2 code (J. Huba, JGR 2000)

E-field from Rostogi –Klobuchar (1990) technique

2 pm: quiet day



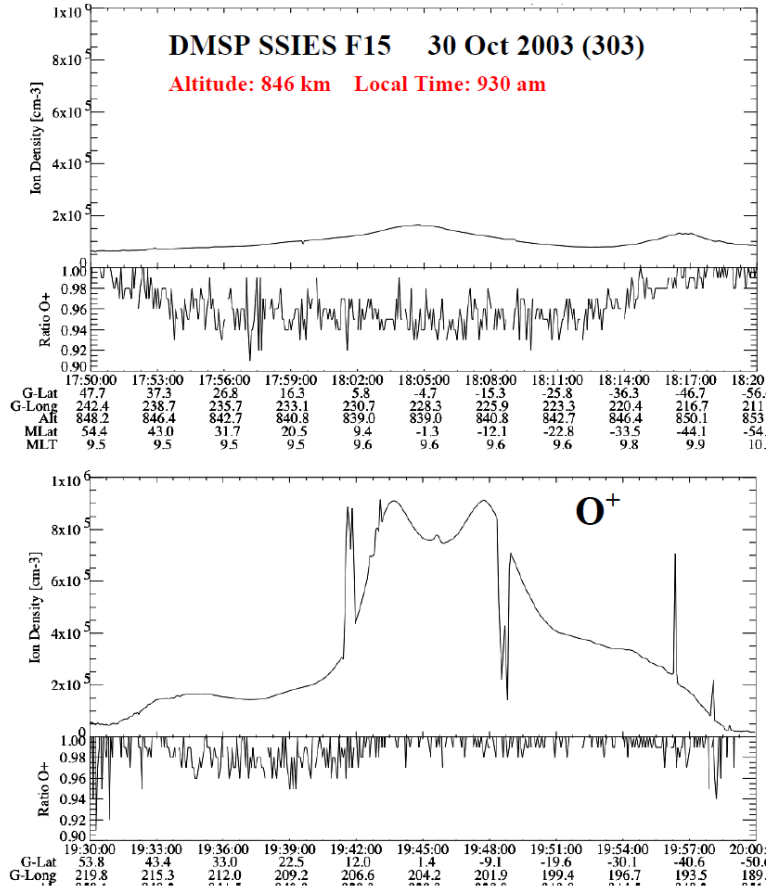
2 pm: 4 mV/m PPEF



This matches Mannucci et al CHAMP measurements within 10%

Verkhoglyadova et al. AGU Mono.vol 181, edited by Kintner et al., 2008

Oxygen ions are lifted up to 846 km during the October 30 2003 storm by the Prompt Penetration Electric Field (PPEF)



Tsurutani et al., ILWS 2006

The oxygen ion densities will cause substantial satellite drag

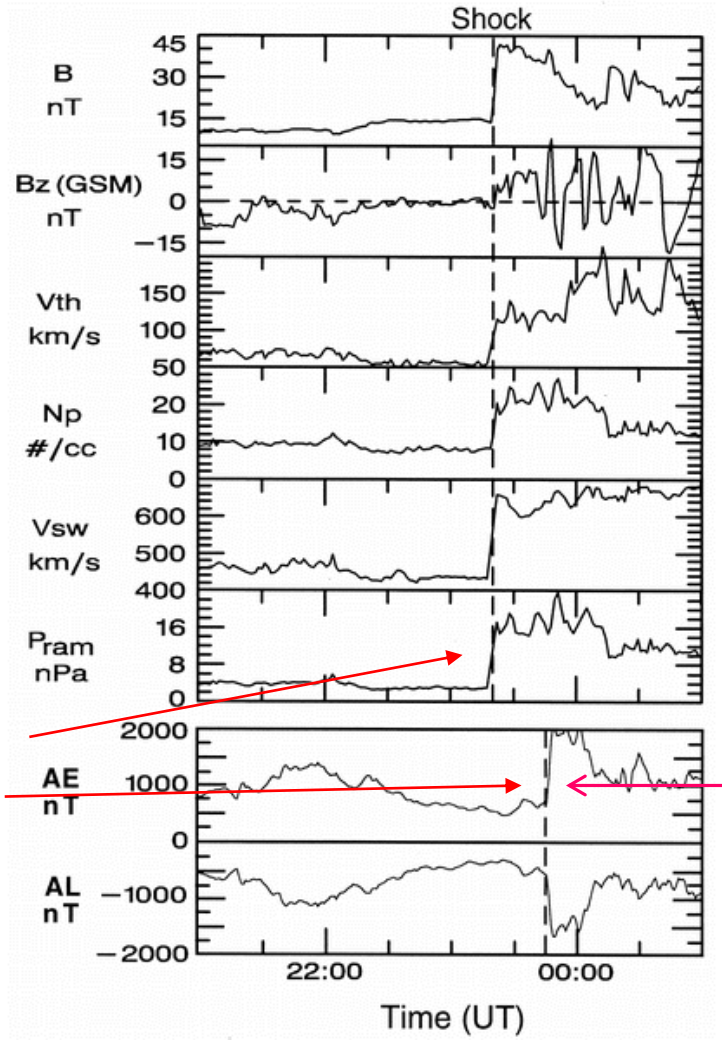
Questions for SWARM

During a large magnetic storm can the satellite drag over the equator be measured?

If so, is the drag factor larger than over the auroral zone regions?

Can the uplift of oxygen ions cause atmospheric neutral uplift as well, enhancing the satellite drag factor? This latter item is a cutting-edge topic.

Interplanetary Shocks can cause dayside aurora (and trigger nightside substorms)



Propagation time delay

$\Delta N/N = 2.0$

$\Delta V_{sw}/ V_{sw} = 0.45$

$\Delta P_{ram} = \sim 4.0$

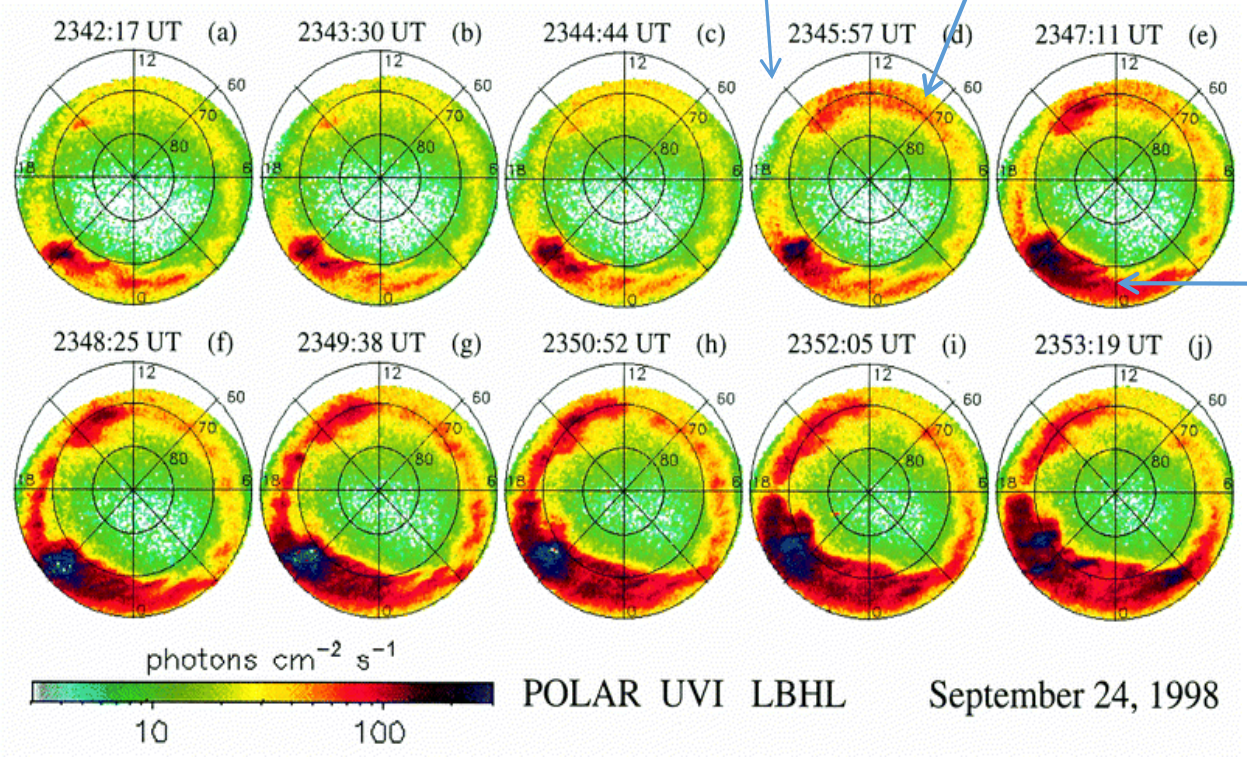
substorm

Zhou and Tsurutani, JGR 2001

Interplanetary Shocks Cause Dayside Auroras and also Trigger Nightside Substorms

Shock arrives at magnetosphere

Shock (dayside) aurora



Triggered nightside substorm

Zhou and Tsurutani JGR, 2001

Question

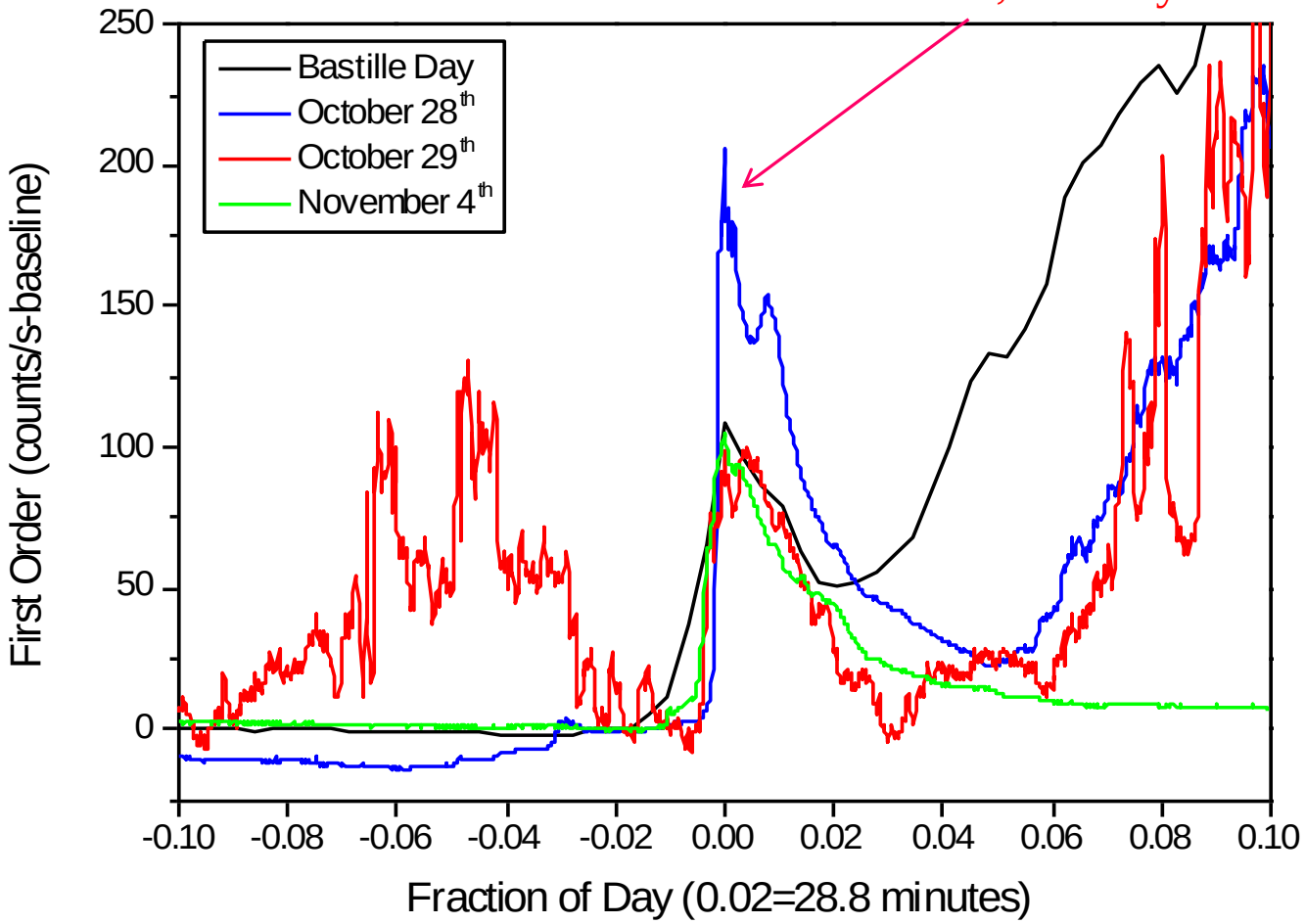
It is known that there are field-aligned currents detected during dayside shock auroras. What do the current systems look like?

Is there a dayside auroral zone ionospheric electrojet?

Is there a global current system? If so, what does it look like?

28 October, 2003 :the Largest EUV Solar Flare in Recorded History. Largest in X-rays Also?

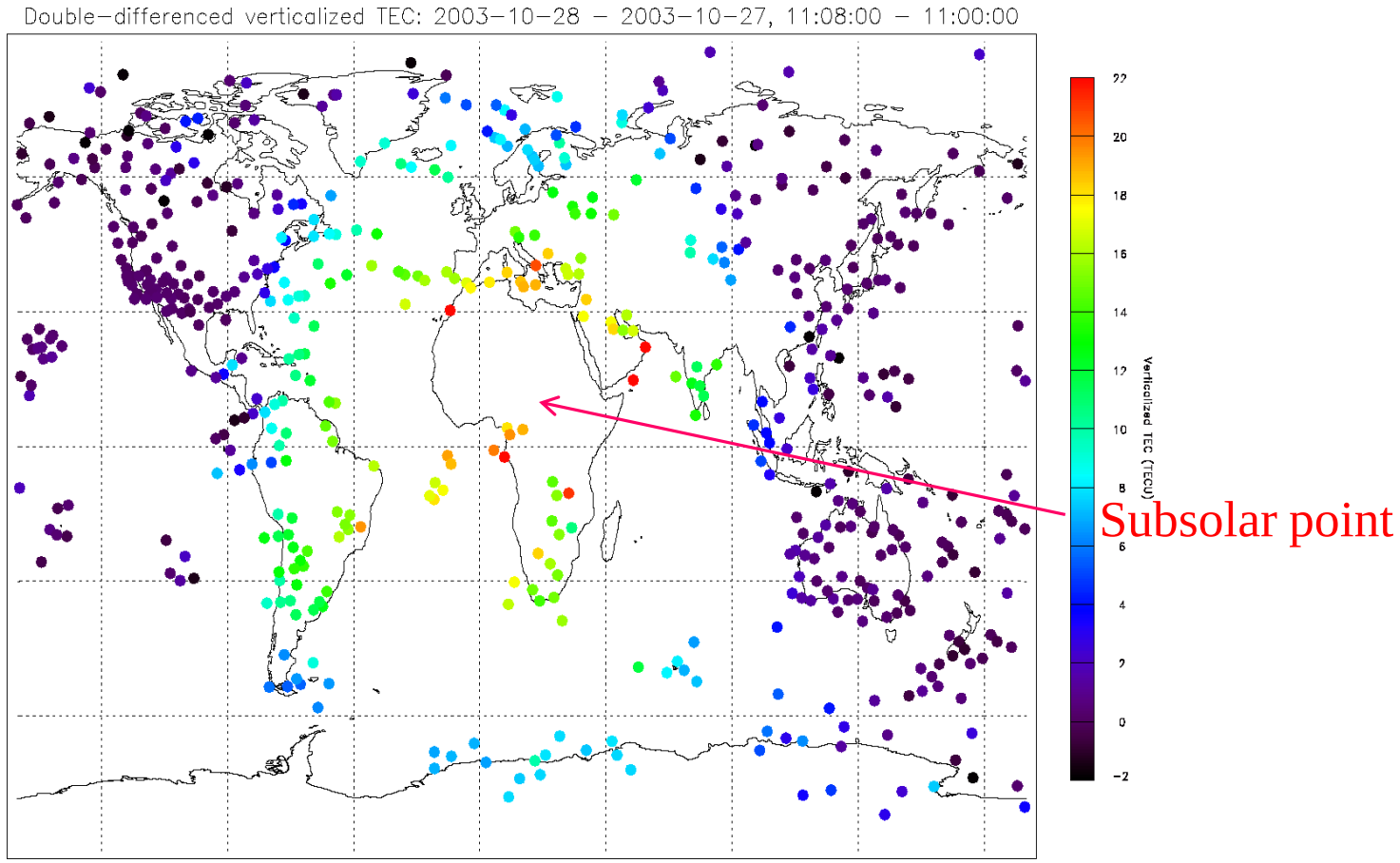
Estimate: X17; Possibly X45? (Thomson et al., GRL, 2004)



Note all x-ray detectors were saturated for event. Thus X-values are only estimates

Tsurutani et al. GRL 2005

Delta-TEC from Ground GPS Receivers for 28 October, 2003 Flare

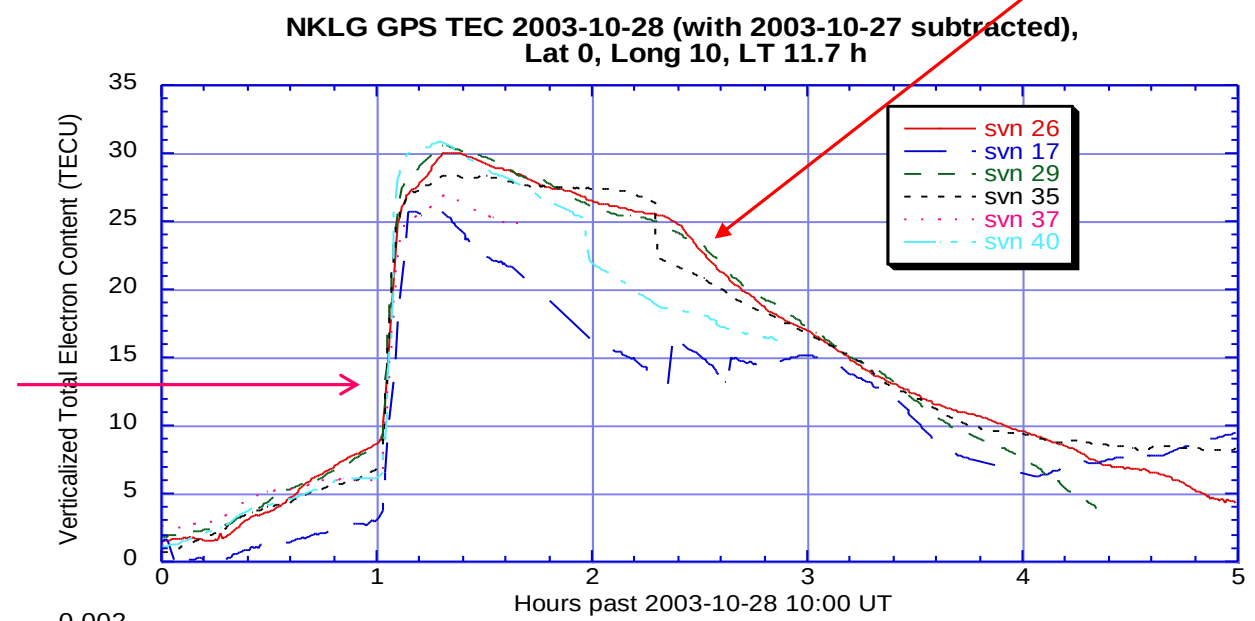


This flare caused a ~30 % Total Electron Content (TEC) increase in the ionosphere

Tsurutani et al. GRL 2005

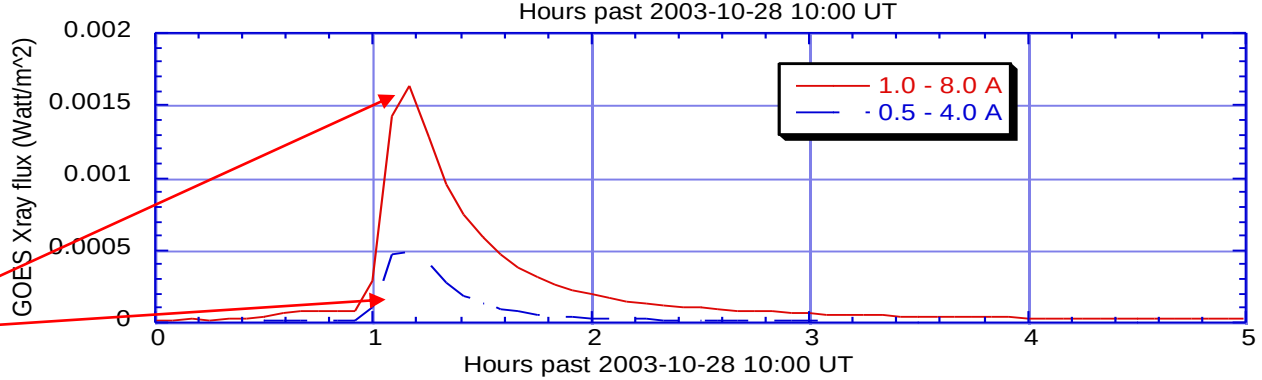
Oct 28, 2003

30% TEC jump

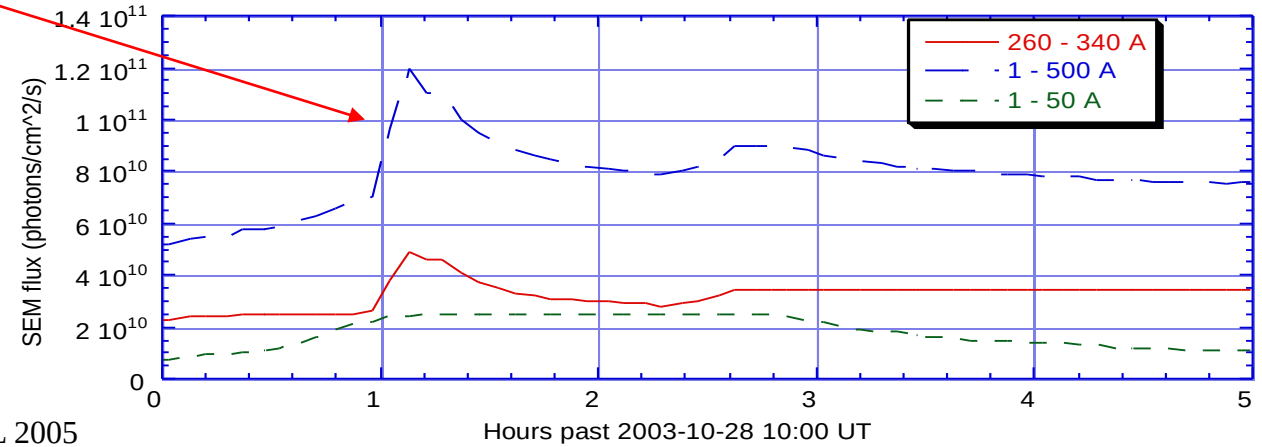


African ground station

Estimated, saturated



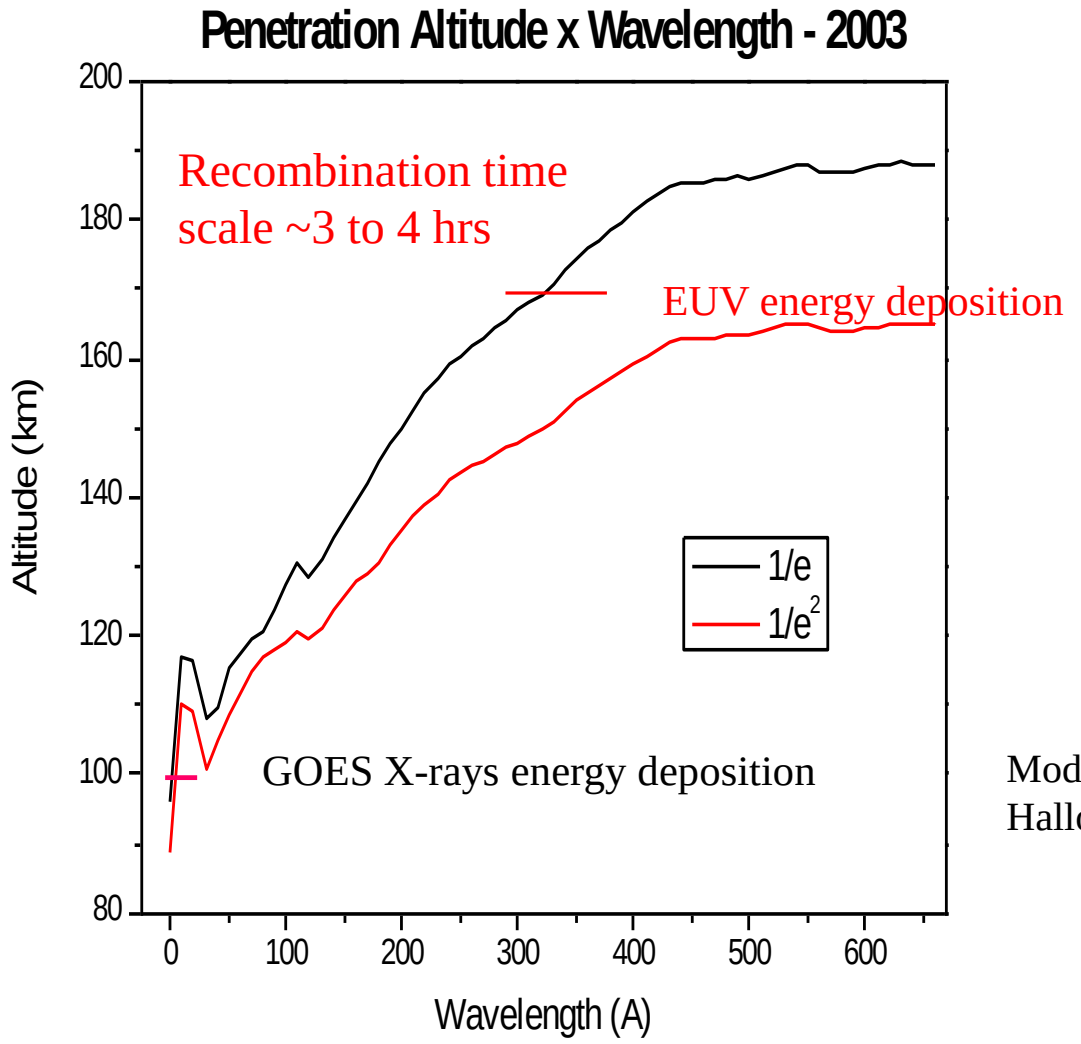
GOES X-rays (modeled)



SOHO SEM EUV

Tsurutani et al. GRL 2005

Recombination time
Scale ~10s of mins



Model atmosphere for
Halloween Day events

Questions

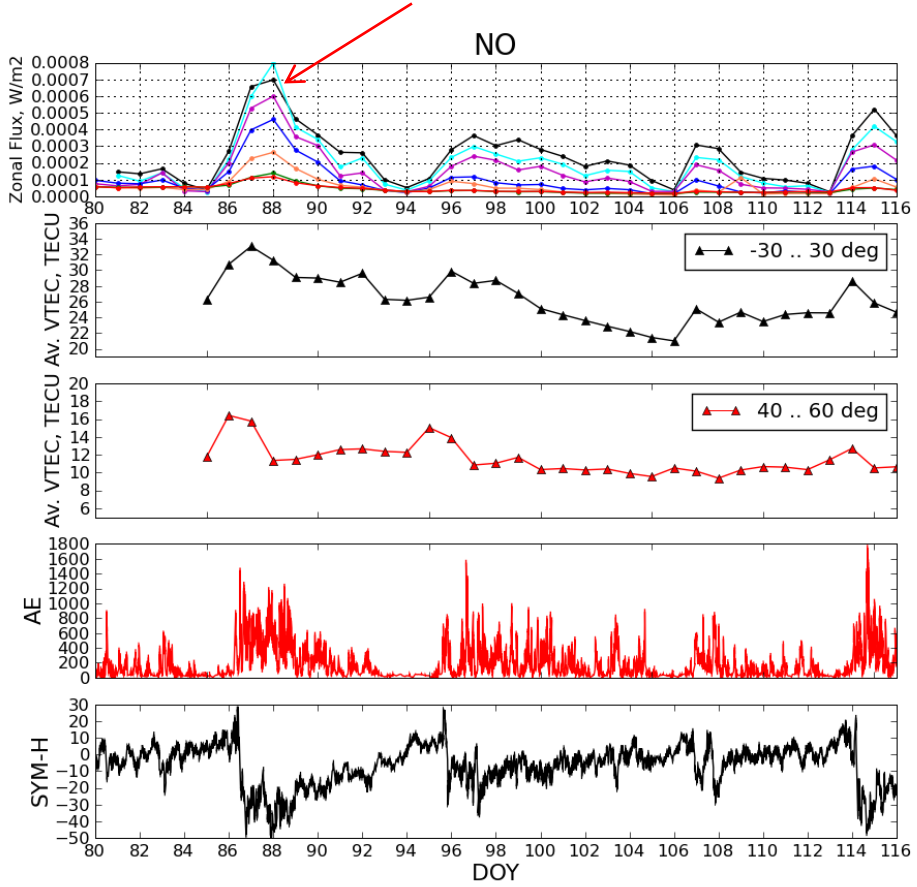
With the enhanced ionospheric densities due to a solar flare, is the EEJ current affected? Will this be measurable from the ground?

Could this be a new technique for studying the EEJ?

Thank You for Your Attention

A series of high speed streams and heating in the auroral zones and TEC at low and mid latitudes. The primary effect is in the auroral zones. A smaller equatorial effect is noted but not understood

Radiation highest in auroral zone



Irradiated
Zonal flux

TEC, low latitudes
(12-14 LT). Enhancements caused by PPEFs?

TEC, mid latitudes
(12-14 LT)

Verkhoglyadova et al. JGR 2011